Solar Shading Products and their effect on Overheating, Well-being, Productivity, and Sustainability in the UK Built Environment.

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ABSTRACT

Blinds and shutters have long been identified as effective methods of attenuating daylight, reducing glare, and managing the thermal gains and losses through the glazing in a building. Shading products can provide energy savings and alter the internal environment to improve occupant comfort. Changes in occupants' perceptions of their comfort can have a subsequent effect on their perceived health, well-being, and actual productivity. Currently, the extent that differing shading products reduce internal temperature increase in UK homes is not well understood. Furthermore, the way shading products alter the internal environmental conditions overall and how these variations affect an occupant's health, well-being, and productivity has not been fully investigated.

If shading products are used to obtain the various performance benefits, they require occupants to operate (open and close) them effectively. More sophisticated shading products incorporate motors and sensors to improve the operation of such products. These systems require a large number of natural resources, so an assessment is needed to identify whether the operational energy savings provided from the use of shading products outweigh the environmental impact of the products themselves throughout their lifetime.

To explore these gaps in research, three real-world, two laboratory, and one desktop study were conducted. Two of the real-world studies were carried out in domestic buildings (an apartment and a semi-detached house) and the third was conducted in a non-domestic office. Data was collected when the shading products were extended and retracted, and statistical analysis was used to compare the data. In the domestic studies, quantitative data were collected relating to the internal temperature conditions. In the non-domestic study, quantitative and qualitative data were collected relating to the changes in a broader range of internal environment conditions and the experiences of the occupants in open and closed blind conditions. This included investigating occupants' perceptions of comfort, health, well-being, and their subjective and objective productivity.

The domestic studies showed that when internal and external shading products were closed, there was a significant reduction in internal temperature increase when comparisons were made between a room with and without shading. Shading products mitigated overheating risk, suggesting that they can improve the thermal comfort of building occupants in warmer weather conditions in UK homes. Of the two system types tested, external shading was most effective. The non-domestic study results confirmed there are both positive and negative benefits to having shading products extended in warmer conditions. The objective productivity of occupants was both negatively and positively affected and this differed depending on the type of task or cognitive function being tested.

The two laboratory-based studies investigated the acoustic performance of internal shading products which are conventionally installed in UK buildings. This investigated the impact they have on sound reverberation and the acoustic transmission of sound. Overall, the results showed internal shading products can reduce reverberant sound and how they are installed (specifically the distance from the window) affects the amount of reverberant sound absorbed. It also identified differing fabrics have different capabilities in reducing sound transmitted into buildings. However, further research is needed to quantify the impact of the transmissive properties of shading fabrics when installed in a real building.

The desktop study involved a screening Life Cycle Assessment (LCA) of an external automated Venetian blind, an internal motorised roller blind and an internal manually operated roller blind. The LCA incorporated the real-world semi-detached house previously investigated as part of the functional unit to carry out the LCA. The operational energy savings of the different types of shading products assessed were stepped as the energy saving potential of shading products varies depending on how they are used and operated. The comparative analysis of the three shading systems suggests the control strategy (automated, motorised, or manual) alters how much operational energy needs to be saved and how long the shading product must be installed for before it becomes environmentally neutral and then environmentally beneficial.

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GLOSSARY

Correlation	A statistical technique that can show how strongly pairs of variables are related.
Degrees of Freedom	The number of values in the final calculation of a statistic that are free to vary.
dB (dBA or dBC)	Decibels, a unit measure of the intensity of sound (A-weighted decibels or C-weighted decibels).
Dependant Variable	The variable whose variation is being studied.
G-value	Solar Energy Transmittance, (also known as Solar Factor) a coefficient used to measure the solar energy transmittance of a window. Ranging from 0 to 1, with 0 representing no solar energy transmittance.
Independent Variable	The variable that is changed or controlled in a scientific experiment.
Milli-point	A simplified metric that represents the average environmental impact of 1 European Person per year. 1 million milli-points (mPt) is equivalent to 1,000 Ecopoints which represents the average environmental impact of 1 European Person per year.
Multicollinearity	A statistical term that refers to a phenomenon in which one predictor variable in a multiple regression model can be linearly predicted from others with a substantial degree of accuracy.
Octave Bands & One-Third Octave Bands	Octave Bands divide the audio spectrum into ten equal parts. The centre frequencies of these bands are 31.5 Hz, 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz, 8 kHz, and 16 kHz. One-third octave bands subdivide these bands into 33 bands.
Paired t-Test	A statistical procedure used to determine whether the mean difference between two sets of observations is zero.
Predictor	A variable used in regression to predict another variable.
Regression	A statistical method that tries to determine the strength of the relationship between one dependent variable and other changing variables (known as independent variables).
R-value	Thermal Resistance, measure of resistance to heat flow through a given thickness of material, m^2K/W.
Significance Level	Statistical significance is the likelihood that a specific difference between two conditions is not due to random chance. A result of an experiment is said to have statistical significance, or be statistically significant, if it is likely not caused by chance for a given statistical significance level (or "confidence level"). For example, a result of $p < 0.05$ means that there is less than a 5% chance that the difference observed between the two conditions was due to random chance.
Stroop	A psychology test where the delay in reaction time between automatic and controlled processing of information is measured. This is caused when the names of words interfere with a person's ability to name the colour of the word used to present the words.
Test Battery	A combination of tests and questions.
U-value	Thermal Transmittance, rate of heat transfer through a structure divided by the difference in temperature across the structure, W/m^2K.
Visual Analogue Scale (VAS)	A question presented on a sliding scale with an associated response representing each extreme of the scale. The respondent is asked to either move a slider or draw a line on the scale to reflect their response.
Working Memory	A cognitive system with a limited capacity that is responsible for temporarily holding information available for processing. Working memory is important for reasoning and the guidance of decision-making and behaviour.

ABBREVIATIONS AND ACRONYMS

ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
BBSA	British Blind and Shutter Association
BIM	Building Information Modelling
BMS	Building Management System
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
CIBSE	Chartered Institution of Building Services Engineers
CCC	Climate Change Committee
DECC	Department of Energy and Climate Change
DV	Dependant Variable, also see Glossary
EPBD	Energy Performance Building Directive
EPD	Environmental Product Declaration
ESSO	European Solar Shading Organisation
GHA	Good Homes Alliance
GHG	Green House Gas (Emissions)
GWR	Glazing to Wall Ratio
IEQ	Indoor Environment Quality
IV	Independent Variable, also see Glossary
ktoe	Kilotons of Oil Equivalent
kWh	Kilowatt-hours
LCA	Life Cycle Assessment
LEED	Leadership in Energy and Environmental Design
MHCLG	Ministry of Housing Communities & Local Government
mPt	Milli-point, also see Glossary
Pa	Pascals
POE	Post Occupancy Evaluation
PPM	Parts per million
TVOC / VOC	Total Volatile Organic Compounds / Volatile Organic Compounds
TWh	Terawatt hours
REHVA	The Federation of European Heating, Ventilation and Air Conditioning
RH	Relative Humidity, %
SAP	Standard Assessment Procedure
SD	Standard Deviation
SE(M)	Standard Error (Standard Error of the Mean), the statistical accuracy of an estimate.
SPL	Sound Pressure Level
UKGBC	UK Green Building Council
WEEE	Waste Electrical and Electronic Equipment
VAS	Visual Analogue Scale, also see Glossary
WGBC	World Green Building Council
WPM	Words per Minute
W/m^2K	Watts per metre squared Kelvin

NOMENCLATURE

A	Sound absorption area of a room (m^2), see Equation 12 [p. 333]
$\boldsymbol{a}$	Constant, see Equation 7 [p. 158]
b	Constant, see Equation 7 [p. 158]
C	Adjustment of sound for (living activity) noise (dB)
c	Propagation speed of sound in air (m/s), see Equation 12 [p. 333]
f	Frequency of sound (Hz)
g	Solar Energy Transmittance, ranging from 0 to 1, with 0 representing no solar energy transmittance, see G-value in Glossary.
H	Cooling power of a Kata Thermometer, see Equation 7 [p. 158]
h	Number of hours of overheating, see Equation 5 [p. 76]
k	Suggested acceptable range (°C), see Table 7 [p. 76]
L	Reference value for the Weighted Sound Reduction Index (dB)
m	Power attenuation coefficient, see Equation 12 [p. 333]
mrt	Mean radiant temperature, measure of the average temperature of surfaces surrounding a particular point (°C), see Equation 1 [p. 59]
LAeq	Leq value measured with an A frequency weighting (also see Leq) (dB)
Leq	Equivalent continuous sound level measured over a stated period of time e.g., $Leq_{,1hr}$ (dB)
R	Sound Reduction Index, a measure of the reduction in the intensity of sound which passes through a material (dB)
R^2	A statistical term used to explain how close the data are to the fitted regression line and the variation of the dependent variable that is explained by the independent variables
R Change	The change in R^2 when additional independent variables are added to a regression model
RT	Reverberation time, seconds (s)
S	Surface temperature (°C)
s	Sample Area (m^2)
T	Air temperature (°C)
V	Volume (m^3)
v	Air velocity, (m/s)
W	Weighted
WF	Weighting Factor, see Equation 5 [p. 76]
α	Absorption, measured on a scale of 0 to 1
Std. β	Standardised β coefficient, standardised coefficient that refers to how many standard deviations a dependent variable will change per standard deviation increase in the predictor variable.
ε	Difference between mean Kata temperature and Air Temperature, see Equation 7 [p.158]
Θ	Operative temperature (°C)
ρ	Reflection, measured on a scale of 0 to 1
τ	Transmittance, measured on a scale of 0 to 1
Δ	Temperature increase (°C)

Superscripts and Subscripts:

e	Solar (energy)
glaz	Glazing
int	Internal
min	Minimum
max	Maximum
mf	Average of the mid-frequency octave bands for 500, 1000 and 2000Hz (s)
mullion	Mullion of a window frame
n	Number of hours, see Equation 5 [p. 76]
n-dif	Diffuse
n-n	Direct
od	Daily mean, see Equation 4 [p. 75]
pi	Practical sound absorption coefficient for the i^{th} octave band, see Equation 15 [p. 333]
rm	Exponentially weighted running mean, see Equation 4 [p. 75]
s	Surface area of fabric in square meters, see Equation 14 [p. 333]
sample	Sample or test specimen, see Equation 13 [p. 333]
tot	Total
tr	Adjustment of sound for traffic noise, dB
upp	Absolute maximum temperature, see Equation 6 [p. 77]
v	Visible Light
w	Weighted
1hr	Hourly (average) measurement
-1	Day previous, see Equation 4 [p. 75]
ε	Exceedance, see Equation 5 [p. 76]

CONTENTS

CHAPTER 1. INTRODUCTION

Blinds and shutters are incorporated in UK building design primarily to attenuate daylight and reduce issues of glare from incoming solar irradiance through the glazed element of a buildings façade. Shading products can also be used as a way of dynamically improving the thermal properties of a window. When shading products are extended in colder weather conditions, they reduce heat losses through windows and when extended in warmer weather conditions they reduce incoming solar gains (BBSA, 2015; CIBSE, 2006a; ES-SO, 2018b; Wouter et al., 2010) Improved management of the thermal gains and losses of a building can provide significant energy savings as the energy required to maintain occupant thermal comfort can be reduced (ES-SO, 2014; Littlefair, 2017b; Wouter et al., 2010). Similarly, shading products can enable buildings to utilise natural daylight and reduce the energy required for electric lighting (Lee et al., 2013; National Energy Foundation, 2016).

In the UK, the current demand for air conditioning in domestic homes is low. Less than 3% of homes were reported to have air conditioning installed in 2012 (BRE and DECC, 2013). However, this is expected to increase as climate change worsens and the number of warmer weather events and the average external air temperature increases (MHCLG, 2019b, 2019c). There is also evidence to suggest that both the uptake and current cooling demand used in non-domestic buildings is increasing (BRE, 2016). Presently internal shading products are installed more frequently in the UK than external shading systems and these are often installed when furnishing the building which can restrict the type of shading product that can be installed. A better understanding of the extent that differing solar shading products (internal and external) have on reducing internal temperatures in typical UK buildings may prove beneficial in illustrating to stakeholders in the design of buildings the importance of considering the installation of solar shading products earlier in the design process.

When vertical shading products are operated (opened and closed) they alter a variety of internal environmental conditions. They can simultaneously affect the visual, thermal and (in some instances) the acoustic conditions and consequently may alter an occupants' perception of their comfort, health and well-being (ES-SO, 2018b; Littlefair, 2017b; National Energy Foundation, 2016). Improvements in occupant comfort, health and well-being are acknowledged to positively affect an occupant's objective and subjective productivity (Wargocki et al., 2006; WGBC, 2016a). This in turn provides a financial incentive for building owners and designers to improve the design and operation of buildings. No study to date has evaluated what the combined effect of extending and retracting shading products has on an occupants' perception of comfort, health, and well-being and how this may subsequently affect an occupants' productivity. Even though extensive investigations into how differing environmental conditions (e.g., visual, thermal, air quality and noise) affect occupants have been carried out, these are often only investigated in isolation of one another. Extending and retracting shading products will likely have both a positive and negative effect on an occupants' perception of their comfort as there may be a conflict in trying to achieve their various needs. For example, the desire for daylight will lead to occupants wanting shading products retracted (open) but their desire for better thermal comfort particularly during hot days will lead them to wanting them extended (closed).

Manually operated shading products are considered a passive measure in reducing energy consumption (Gupta et al., 2015) and have a low environmental cost over the span of the products lifetime as determined by Life Cycle Assessments (LCA) (Andrews et al., 2015, 2016). However, more sophisticated systems are available on the market that require a small amount of energy to operate them (Littlefair, 2017a). Motorised systems are operated more frequently than manual systems and are believed to provide greater energy savings than manual shading systems due to their increased use (Paule et al., 2015). When motorised shading systems are combined with sensors that monitor either internal or external environmental conditions the data collected can be used to help determine what position the shading should be in (open or closed). These are referred to as automated shading systems even though a user-override is often provided (i.e., a switch to operate the shading product and override the automated algorithm). Automated shading products can dynamically adapt their position based on the varying environment conditions which can result in improved thermal and visual management of glazed facades. These are of particularly useful when occupants are not present in the room or building but are only effective if the control algorithm is implemented appropriately (IEA, 2013; Littlefair, 2017a). However, the increased complexity of the components and materials needed in these products (e.g., motors and sensors) mean they will have a higher environmental impact in terms of embodied carbon and associated environmental impacts. Therefore, these innovations in shading products require a Life Cycle Assessment to be carried out to identify if the environmental benefits provided through increased operational energy savings throughout the product's lifetime outweigh the additional environmental impact of the more complex shading product.

In summary, existing literature suggests that solar shading products have the potential to affect environmental, economic, and social issues present in buildings. Operated in the right way they can improve the energy efficiency and reduce the environmental impact of buildings as well as improving the comfort, health, well-being, and productivity of occupants that live and work in UK buildings. However, the benefits that can be provided have not all been proven with robust scientific research and may not all be achievable simultaneously. Therefore, this thesis aims to contribute to this knowledge through a range of real-world studies supported by laboratory experiments to help answer the following research question:

Is there a sustainable benefit to installing and using solar shading products in homes and offices in the UK?

CHAPTER 2. LITERATURE REVIEW

2.1 European and UK Building Targets

The UK government increased the target to reducing its greenhouse gas (GHG) emissions from 80% to 100% (from 1990 levels) by 2050 in 2019 (The UK Government, 2019) based on recommendations from the Climate Change Committee (CCC, 2019a). Prior to the UK's exit from the EU, the European Commission published the Energy Efficiency Directive (EED) (European Commission, 2018a) and the Energy Performance of Buildings Directive (EPBD) (European Commission, 2018b) which outlined a legislative framework to improve the building stock across the EU. The EED sets out several measures to help the EU reach its overall goal of improving energy efficiency by 20% by 2020 and 32.5% by 2030 (European Commission, 2018a) including the rollout of smart meters, renovation of 3% of government buildings and the energy labelling of household products. The EPBD requires all new buildings to be nearly zero energy by the end of 2020 with long-term renovation plans for the rest of the building stock amongst other additional measures and policies (European Commission, 2018b). The European Commission has published recommendations of how to renovate the building stock for improved energy efficiency whilst considering how to adapt buildings for climate change. These recommendations include the installation of shading products to protect buildings from overheating during warmer weather events and reduce the need for active cooling (European Commission, 2019).

To incentivise progress in producing net zero carbon buildings London has signed up to the World Green Building Council (WGBC) Net Zero Carbon Buildings Commitment which encourages buildings (within its organisational power) to be net zero carbon in operational energy by 2030 and advocates that all buildings should be net zero carbon by 2050 (WGBC, 2016b). To support these targets the UK Green Building Council (UKGBC) launched the 'Advancing Net Zero - Net Zero Carbon Building Framework Definition', a programme which encourages mitigation of operational energy and whole life embodied carbon during building construction, operation, end-of-life and beyond the lifecycle (UKGBC and Advancing Net Zero, 2019). Whilst this framework is voluntary, large stakeholders within the UK Building sector have made commitments to meet the framework goals (UKGBC, 2019).

2.2 Energy Efficiency in UK Domestic Buildings

In the UK energy is consumed by four main sectors: transport, industry, services, and domestic homes. In 2017 these sectors consumed 40%, 16%, 15% and 29% respectively (DBEIS and ONS, 2019a). Within domestic homes 39,874 ktoe was used in 2017 for hot water, space heating, cooking, lighting, and electrical appliances. 64% of this energy was consumed for space heating, 17% for hot water, 14% for electrical appliances and 3% for lighting and cooking (Office for National Statistics, 2019). Domestic energy consumption is most susceptible to fluctuations in external air temperatures as ≈ 80% of energy consumption is related to either space heating or hot water. The building envelope is highlighted as an area where substantial improvements resulting in energy savings and lower CO_2 emissions can be made (IEA, 2013).

The social expectation for warmer internal temperatures has contributed to the prevalent use of space heating systems. In 1970, internal average temperatures of homes with central heating were estimated to be 13.7°C in winter, this average rose by 4°C by 2011 to 17.7°C. This rise in average internal temperatures in UK homes is attributed to the increase in installing central heating which rose by 90% within 40 years (DECC, 2013). Whilst overall energy use has increased since 1970 because of the increase in the number of households[1], the actual energy use per household has declined. An analysis carried out on data collected between 1970 and 2012 suggests that energy use has fallen from 23,800 kWh to 18,600 kWh (DECC, 2013). More recently the mean annual energy consumption was reported as 17,500 kWh per annum per household in 2018 (DBEIS and ONS, 2019b). These reductions in energy use are related to improvements in insulation and airtightness standards and improved lighting and heating systems efficiencies (DBEIS and ONS, 2019a). Insulation standards for walls, roofs and flooring have significantly improved with a typical cavity wall now providing a U-Value of 0.2 W/m^2K. In 2017, 85% of English homes had full double glazing which provides an improvement of 5.8 W/m^2K to 2.9 W/m^2K in heat losses for the window area (MHCLG and ONS, 2019). Incorporation of low emissivity coatings, increase in cavities, use of inert gases (e.g., argon), reducing thermal bridging and increasing the number of glazed panels can further reduce U-Values to 1.00 W/m^2K. The limiting fabric standard in UK Building Regulations for new domestic buildings is 2.00 W/m^2K and for new

[1] The number of households increased in the UK by more than two-fifths between 1970 and 2012 and increased by 45% between 1970 and 2017, from 18.8 million to 27.2 million (DECC, 2013; Office for National Statistics, 2018).

non-domestic buildings is 2.20 W/m^2K (HM Government, 2010b, 2010a). However, for domestic homes to meet the Target Emission Rate (TER) they are recommended to have windows that have a U-value of 1.4 W/m^2K and 1.6 W/m^2K when being renovated (HM Government, 2010c, 2010a). Even though improvements to the insulative properties of our homes are beneficial for energy efficiency in the heating season (autumn and winter) increased insulation and airtightness has been widely acknowledged to exacerbate overheating issues in warmer weather periods. This is a result of the UK experiencing higher external air temperatures and more frequent hot weather events (i.e., heatwaves) due to climate change (Zero Carbon Hub, 2015).

2.3 Energy Efficiency and Green Building Design in Non-Domestic Buildings

In recent years the Climate Change Committee (CCC, 2015, 2019b) has reported that energy savings have stagnated in the commercial sector. It is approximated that there are 2 million non-domestic buildings that contribute to producing one fifth of the nation's annual CO_2 emissions (Armitage et al., 2015) and whilst various incentives/policies have been introduced they have failed to encourage business owners to make investments that help reduce the energy consumption of their buildings. The WGBC (2013) produced a 'business case' for 'green building design' to highlight the financial benefits of investing in energy efficiency for non-domestic buildings. Various benefits were revealed such as lower operating costs; increased marketability and asset value; potential equal cost comparison between sustainable and conventional builds; and improvements in the health, well-being, and productivity of staff.

Improving staff productivity yields many benefits for commercial organisations, as these improvements provide almost immediate financial returns on investment. Staff costs tend to account for 90% of a business' expenditure where energy costs only account for 1%. Therefore, there are greater financial returns on increasing staff productivity than there would be on reducing energy consumption (WGBC, 2014). This is considered a valuable driver for improving the energy efficiency of commercial and other non-domestic buildings. It has been quantified that as little as a 1% increase in performance can offset the annual costs of mechanically ventilating a building (Clements-Croome, 2008; Wargocki et al., 2006). In addition, the payback time of investment in improving the Indoor Environment Quality (IEQ) is generally less than 2 years (Wargocki et al., 2006). A further study conducted by Harvard University found evidence that workers in green certified buildings (LEED) achieved higher cognitive function scores (26%) and have 30% fewer sick days than those in non-certified buildings (MacNaughton et al., 2017). Improvements in health, well-being and productivity provide a vital way in encouraging this sector to reduce its CO_2 emissions as there is a quicker return on investment and greater economic benefit on offer (WGBC, 2016a).

In the report 'The Business Case for Green Buildings' (WGBC, 2013) it was emphasised how the first generation of 'green building design' centred around improvements in energy and resource efficiency whereas now 'green building design' requires consideration of not only the environmental and economic impacts of a building but also the social and economic impacts, which is considered a more 'holistic' approach towards building design. Interpretations of what should be considered in a 'holistic' building design vary and are encouraged primarily through voluntary building certification. Voluntary building certificates aim to deliver more sustainable buildings through providing a holistic framework of assessment where certain criteria must be fulfilled during the building's lifetime. The criteria are assessed during building design, construction, and in-use. The world's first scheme was developed by the Building Research Establishment (BRE) called BREEAM. The BREEAM scheme (BREEAM, 2018) assesses a variety of aspects linked to sustainability including energy consumption, land use, materials, health and well-being, water, waste, pollution, transport and innovation. Depending on the scheme selected various requirements need to be fulfilled to collate points to pass. Some of these points are statutory and others are optional, but a certain number of points have to be obtained in each of the assessment areas. More recently developed certification schemes have focused more on the health, well-being and comfort of occupants through carrying out detailed Post Occupancy Evaluations (POEs) (Ward et al., 2017). The WELL building standard (WELL, 2019) and the NABERS assessment (NABERS, 2019) are two of the more popular schemes, the former originated in America and the latter in Australia. What differs between these certification schemes and others is that the buildings are periodically evaluated, creating a culture of continuous evaluation and improvement. The NABERS assessment also covers aspects of energy efficiency by benchmarking performance against other similar buildings and publicly declaring the performance of the building with future targets to reduce energy consumption.

2.4 Climate Change and Energy Efficiency

The UK Climate Change Risk Assessment 2017 warns that the UK currently 'has no comprehensive policies in place to adapt existing homes and other buildings to high temperatures, manage urban heat islands, nor safeguard new homes' (CCC, 2016). In 2018, the Environmental Audit Committee put evidence to government that identified the health risks of heatwaves and the reasons why change was needed. The most notable evidence to health was the impact of the 2003 heatwave. This lasted for ten days in the UK and caused 2,193 heat-related deaths. The current average number of deaths per year is expected to more than triple by 2050 to 7,000 fatalities a year (House of Commons Environmental Audit Committee, 2018; Zero Carbon Hub, 2015).

In the UK numerous non-domestic buildings enlist the use of mechanical cooling systems to keep temperatures within comfort thresholds in summer. A study by the Building Research Establishment (BRE) showed that in the ten years (up to 2016) energy use for air conditioning had increased by 45% from 20TWh to 29TWh accounting for one tenth of the UK's electricity consumption (BRE, 2015). Currently within UK domestic buildings the use of mechanical cooling is rare (unlike many EU countries). A survey carried out in 2011 on behalf of the Department for Energy and Climate Change (DECC) found that 43% of homes used portable fans, 9% used fixed fans and 3% used air conditioning to reduce internal temperatures in summer (BRE and DECC, 2013). The report found that 20% of households had an issue with overheating in one or more rooms of their home in summer months. Interestingly, a bi-variate analysis suggested that those in more energy efficient homes (e.g., a SAP rating > 70), located in urban areas and constructed post-1990 were more likely to overheat (BRE and DECC, 2013).

A more recent study by the Ministry of Housing, Communities and Local Government (2019b) predicted that by the mid-2020s the uptake of air conditioning in domestic homes in England will increase by up to 34%, and by the mid 2050's will increase by between 6 and 56%. The variation in uptake is dependent on building location due differences in local climate conditions. The uptake of air conditioning was based on the overheating risk present in new homes in Southampton, Nottingham, and London. For example, its expected there will be a 0% increase in air conditioning in Nottingham by the mid-2020s as the climate is cooler but in London its predicted there will be a 34% increase. London's climate is warmer than that of Southampton and Nottingham and therefore homes will be more susceptible to overheating. These predictions were followed by prediction models of the energy required to keep homes thermally comfortable with air conditioning. Three building typologies, a semi-detached and a dual aspect and single aspect apartment, in the three locations in England were reviewed. The study identified an average of 2,016 kWh of additional electricity per annum per dwelling would be required by 2020, increasing to

2,565 kWh per annum per dwelling by 2050 (based on DSY 2020 and 2050s weather data) (MHCLG, 2019c). If 34% of homes in the UK required air conditioning to maintain thermal comfort this could potentially lead to an additional energy requirement of up to 16.5 TWh by the mid-2020s based on the existing 23.9 million domestic homes in England (MHCLG, 2018). This research suggests that in the future there may be a shift in the energy used in UK domestic buildings from solely heating energy to heating and cooling energy if the building stock is not designed to be more resilient to climate change. The additional energy requirement needed in UK homes for cooling and the increasing energy use for cooling in non-domestic buildings will subsequently have a negative impact on the UK achieving its energy target commitments, making reaching the net zero carbon targets more challenging.

2.5 Productivity, Health, Well-Being, and Comfort

The prime requirement for productivity is that the mind and body are in a state of health and well-being to improve work and concentration (Clements-Croome, 2000). However, obtaining complete satisfaction or comfort of all users in an indoor environment is complex due to the number of variables within the built environment. The environmental constraints alone are confounded by variables of users which are hugely influenced by:

- **Physiology** – e.g., how occupants produce heat or how they interpret light depending on their health, age, or gender.
- **Psychophysics** - e.g., how our brains regulate the body to cope with the surrounding environmental factors.
- **Physics** (between the environment and each occupant) – e.g., glare is relative to positioning of an occupant and direction of light; thermal comfort can also be modified by location of an occupant in relation to air conditioning, windows, clothing level etc.
- **Psychology** (which impacts individual behaviours) – e.g., what clothes occupants choose to wear; how occupants use and feel about available controls; and what posture and activity they impose on themselves within a given environment (Nicol et al., 2012).

There are viable economic, environmental, and societal benefits to be had from improving the overall perceptions of comfort of buildings for occupants. For example, if buildings are not initially designed to be thermally comfortable and are built so they are unable to adapt to variations in temperature, overheating in summer may occur. This can have a negative effect on occupants as when occupants experience temperatures greater than 25°C they are likely to suffer from symptoms associated with heat exhaustion (Clements-Croome, 2018). This is caused when the body's core temperature exceeds its healthy temperature of 37°C (Kjellstrom et al., 2009). Heat related symptoms and illnesses include:

- increased heart rate
- increased respiratory ventilation
- increased end tidal partial pressure of CO_2[2] (Lan et al., 2011)
- decreased arterial oxygen saturation (Lan et al., 2011)
- dehydration due to sweating and inadequate liquid intake (Kjellstrom et al., 2009)[3]

The health impacts associated with warmer temperatures affect those who have poor thermoregulatory systems and/or are unable to identify that they are suffering from heat stress. The elderly, infants, and those with disabilities or chronic illnesses are most susceptible (Public Health England, 2015). Higher temperatures have also been associated with the loss of life and poor health subsequently creating a negative socio-economic effect through straining the UK's health system (MHCLG, 2019a; PHE, 2019).

An occupants' general mood also alters in warmer temperature conditions, and it has been evidenced that occupants:

- became less willing to exert effort and generally felt more negative (Lan et al., 2011; Lan and Lian, 2009).
- reported more negative symptoms relating to Sick Building Syndrome (Fang et al., 2004).
- experienced increased anxiety, which impacts rates of suicide, psychosis, alcoholism, and caloric intake (Parsons, 1993).
- experienced increased feelings of anger (Parsons (1993) citation to Provins, 1966).

Perception of an individual's thermal sensation can then trigger behaviours within an environment to improve their thermoregulation system. These can include passive measures (in terms of energy usage) such as altering clothing, opening/closing windows and/or blinds, posture change, activity change, moving location and when available active measures such as changing thermostat settings, using electric fans or air conditioning

[2] Measure of respiration rates.
[3] A more extensive list is available in Heatwave Plan for England by Public Health England (2015).

(ASHRAE, 2013; BRE and DECC, 2013; Mavrogianni et al., 2017; Nicol et al., 2012). Passive actions are often only initiated when temperatures exceed comfort levels. In some cases, it may only be possible to reduce the temperatures back to comfort levels when external temperatures reduce e.g., via night-time ventilation. Where active cooling is used to maintain comfort levels additional energy is required to maintain these lower temperatures, subsequently increasing energy consumption and the carbon emissions of a building. In domestic settings a reliance on active cooling may also have a damaging effect on those families that are fuel poor.

Those who suffer from poor thermal comfort in work settings are also likely to be less productive (UKGBC, 2016; WGBC, 2014, 2016a). Research carried out on occupants working in increased air temperatures (> 25°C) have been evidenced to:

- have a reduced performance on office-based tasks (Heschong Mahone Group, 2003; Seppänen et al., 2006),
- type more words per minute but make more errors, and
- perform less well on mental arithmetic, grammatical reasoning, processing speed and accuracy and reaction time tasks (Lan et al., 2011).

A meta-analysis of 24 studies related to office task performance also found that air temperatures between 20 - 24°C, with an optimum of 22°C, were 'best' for performance (Seppänen et al., 2006). Additionally, Wyon (1996) found that occupant control over a 4°C range in temperature increased logical thinking by 3% and text typing by 7%.

Within academic research there have been various studies that have examined specific environmental comfort aspects, e.g., thermal comfort, visual comfort, air quality, acoustic comfort, and identified how variations in perceptions of the environment or the objective conditions have subsequently impacted their health and well-being and/or productivity. Table 1 and 2 summarises some of this research and identifies the positive and negative impacts of varying indoor environment conditions on health, well-being, and productivity, however most of this literature emphasises the negative impacts. Additionally, Table 3 provides a list of the recommended thresholds provided by the Chartered Institution of Building Service Engineers (CIBSE) and where applicable the statutory requirements for homes (bedrooms and living rooms) and office spaces (open plan and cellular offices) have been provided.

Table 1. Impact of lighting, view, air quality, temperature, and noise on health, well-being and productivity (1 of 2).

	Detail	Health & Well-being	Productivity	Reference
Lighting	*Lack of access to daylight*	· Increased occupant dissatisfaction associated with the lack of access to a window.		*WGBC, 2014*
	Access to 3hrs daylight	· Reduced occupant dissatisfaction and work stress (observed in nurses).		*Alimoglu and Donmez, 2005*
	Increase of 100 lux	· Reduced hospital stays by 7.3 hrs after coronary artery bypass.		*Joarder and Price, 2013*
	Poor colour rendering	· Increased stress.	· Reduced productivity.	*Seguro and Palmer, 2016*
	Glare		· Negatively affected short/long term memory, short term verbal memory and visual acuity.	*Heschong Mahone Group, 2003*
View	*Lack of view*	· 20% reduced occupant satisfaction when occupants are provided with daylight through a tubular guidance system vs a window with a view.		*Boyce, 2014*
	Provision of natural elements (greenery and sunlight)		· 15% more creative.	*Browning and Cooper, 2015*
Air Quality	*Increase in pollution loads*	· Overall decrease in subjective health.	· 7% reduction in air quality satisfaction. · Increased reporting of headaches. · Reduced levels of subjective effort. · 6.5% reduction in text typing speed.	*Wargocki, 1999*
	Replacing Air Filter, Increasing Outdoor Air Supply & increase in Ventilation Rate	· Improved overall comfort and perceived health and wellbeing.	· Significantly improved performance.	*Wargocki et al., 2004*
	Increased TVOC concentration by 500-$\mu g/m^3$		· Reduced cognitive function performance by 13%.	*Allen et al., 2016*
	400ppm increase in CO_2		· Reduced cognitive function performance by 21%.	*Allen et al., 2016*

Table 2. Impact of lighting, view, air quality, temperature, and noise on health, well-being and productivity (2 of 2).

	Detail	Health & Well-being	Productivity	Reference
Temperature	*Increase in air temperature (between 23 and 24 ℃).*		· Performance of call centre staff reduced by 2%.	*Heschong Mahone Group, 2003*
	Increase in air temperature (between 22 and 30 ℃).		· Reduced performance on office-based tasks by 8.9%.	*Seppänen et al., 2006*
	Increase in Air temperature (between 22 and 30 ℃).		· Less willing to exert effort. · Text typing speed improved but more errors were made. · Mental arithmetic, grammatical reasoning, Stroop with feedback and choice reaction performance reduced.	*Lan et al., 2009*
	Increase in air temperature.	· Symptoms of Sick Building Syndrome more frequently reported.		*Seppänen et al., 2006; Wargocki et al., 2006*
	Occupant control of a 4 ℃ air temperature range.		· 3% increase in logical thinking. · 7% increase in typing performance.	*Wyon, 1996*
	Increase in air temperature and relative humidity (between 20°C / 40%, 23°C / 50% and 26°C / 60% RH).	· Symptoms of Sick Building Syndrome more frequently reported.		*Fang et al., 2004*
Noise	*Increase in external noise.*		· Negatively effects student performance.	*Shield and Dockrell, 2008*
	Poor acoustic comfort.		· Negative impact on memory, problem solving and reading attention negatively affected.	*Goines and Hagler, 2007;*
	Dissatisfaction with noise levels and communication privacy.		· Leading contributor to occupant dissatisfaction.	*Bunn and Marjanovic-Halburd, 2016; Kim and de Dear, 2013*
	Increase in air temperatures (between 20 - 30 ℃) whilst acoustic conditions maintained.	· Increase in subjective annoyance and acoustic comfort.		*Guan et al., 2020*
	Sleep disturbances due to noise.	· Increased blood pressure, heart rate & finger pulse amplitude.		*Stansfeld and Matheson, 2003*
	Reporting of unwanted noise.	· Increased blood pressure & annoyance.		*Stansfeld and Matheson, 2003*
	Continuous exposure to 85-90 dBA.	· Noise-induced hearing impairment.		*Stansfeld and Matheson, 2003*

Table 3. Statutory and recommended indoor environment thresholds for homes and office spaces.

	Homes	Reference	Offices	Reference
Lighting	100 lux bedrooms. 50 - 300 lux living rooms.	*CIBSE, 2015*	300 - 500 lux open-plan & cellular offices. 100 lux minimum requirement for offices.	*CIBSE, 2015*
			200 lux average requirement for offices.	*HSE, 1997*
Temperature	17 - 19°C bedrooms in winter. 23 - 25°C bedrooms in summer. 22 - 23°C living rooms in winter. 23 - 25°C living rooms in summer.	*CIBSE, 2015*	21 - 23°C open-plan & cellular offices in winter. 22 - 25°C open-plan & cellular offices in summer.	*CIBSE, 2015*
Air Quality	13 - 29 $L{\cdot}s^{-1}$ whole house minimum. Varies depending on the occupancy.	*HM Government, 2013*	10 $L{\cdot}s^{-1}$ per person.	*HM Government, 2013*
	40 - 70% relative humidity.	*CIBSE, 2006*	40 - 70% relative humidity.	*CIBSE, 2006*
	950 - 1250 PPM of CO_2.	*BSI, 2019*	950 - 1250 PPM of CO_2.	*BSI, 2019*
Noise	30 dBA / 55 dBC bedrooms. 35 dBA/ 60 dBC living rooms.	*CIBSE, 2015*	35 dBA/ 60 dBC open plan & cellular offices.	*CIBSE, 2015*
			Maximum reverberation time for mid-range frequencies (500 – 2000Hz) < 1 second for offices.	*DfE, 2015*

The data collected within the studies outlined in Table 1 and 2 included:

- *Demographic data* – e.g., age, gender, ethnic background, occupation.
- *Objective environment measures* - e.g., air temperature, mean radiant temperature, air velocities, lux level, dB, CO_2 concentration, design, and layout.
- *Subjective perceptions of the environment conditions* - e.g., subjective surveys.
- *Objective or subjective perception measures of productivity* - e.g., cognitive function and mental ability tests, text typing tests or performance related questions.
- *Objective or subjective perception measures of health and well-being* - e.g., sleep quality, heart rate, skin temperature, health related questionnaires or psychometric questionnaires.

These studies were either conducted in the field or within a laboratory setting and sometimes a mix of the two e.g., a simulated office environment. However, field studies are believed to have more weighting as they have more relevance to normal living conditions (CIBSE, 2015; Seppänen et al., 2006). Within both experimental methodologies' objective environment measures and subjective perceptions are measured consistently, often resulting in a large volume of quantitative and qualitative data being collected during varying external conditions, enabling the diagnosis and analysis of building related problems more efficiently and accurately (Al Horr et al., 2016; BCO, 2016, 2017). This data is then correlated with either objective or subjective measures of health, well-being and productivity collected periodically from occupants to produce a triangulated dataset of results which is considered to provide corroborative evidence (Lan and Lian, 2009). Analysis of mean responses and regression analysis are common statistical methods used to identify what environmental conditions altered perceptions or actual variations in performance and symptoms of health and well-being (Heschong Mahone Group, 2003; Lan et al., 2009). The measurement intervals and specific measures used vary depending on the length of the study, the experimental methodology chosen and the hypothesis of the study.

A similar framework to that used in academic research has been identified as adoptable by commercial companies. The WGBC (2016a) and the British Council of Offices (2017) have outlined these frameworks. However, the metrics for health, well-being and productivity can differ as they try to utilise readily available data often recorded by Human Resources departments (i.e., metadata) as measures of health, well-being and productivity. These include:

- Absenteeism

- Staff turnover / retention
- Revenue
- Medical Costs
- Medical Complaints
- Physical Complaints
- Task efficiency & deadlines

2.6 Solar Shading Products and the UK Built Environment.

Users (inclusive of architects and building specifiers) often choose shading products based on aesthetics, fashion, ease of use and other more emotional motives (Wouter et al., 2010). The functional benefits of shading products are often devalued and become less important. Seguro and Palmer (2016) identified four key areas that highlight the variety of benefits shading systems provide the built environment.

- *Reduction in Energy Consumption* – Space cooling and heating alongside electrical lighting savings can be achieved, providing operational energy savings and reduced CO_2 emissions whilst taking into consideration the impacts of Life Cycle Assessment (LCA) of the product.
- *Compliance with Regulation* – Can help with preventing overheating of buildings and comply with health and safety requirements.
- *Comfort Improvements* – This may be thermally, visually, acoustically or with indoor air quality. All aspects provide occupants with healthier and more satisfactory indoor spaces that can improve overall well-being and productivity.
- *Daylight Utilisation (More Glazing)* – The continuation of design trends producing highly glazed façades which is a focus for “green” building design to improve visual comfort for occupants and improve the aesthetic and biophilic design of buildings.

There are a wide range of benefits to be obtained from the inclusion and appropriate specification of shading products within the UK. However, solar shading products tend to be devalued as remedial solutions because the benefits are poorly understood by industry. Retrofit of solar shading products is more costly than if incorporated at the design stage of a building. This is because retrofitting shading options are constrained by the type of window specified, the physical structure and the appearance of the façade (BRE, 2017b).

2.6.1 Product Variety

Within the UK there are a broad range of shading products available. These are categorised primarily as either ‘Internal’ or ‘External’ shading systems. Figure 1 and Figure 2 are taken from Serguro and Palmer (2016) who evaluated the British Blind and Shutter Associations (BBSA) Trade Database identified the extent of the products available in the UK. Definitions of types of shading products are also provided in BS EN 12216 (BSI, 2018).

Internal shading systems include blinds, shutters, screens, mid-pane blinds, and tensile structures and their sub-groups relate to either product performance characteristics (e.g., dimout, block out, antiglare), physical attributes (e.g., timber, vertical, shaped, non-retractable) or installation locations (e.g., conservatory or roof light). External systems are condensed into the broader categories of blinds, screens, brises soleil, tensile structures, awnings, or glazing. Whilst these categories are useful, all products will have a varying range of product performance characteristics due to their physical attributes.

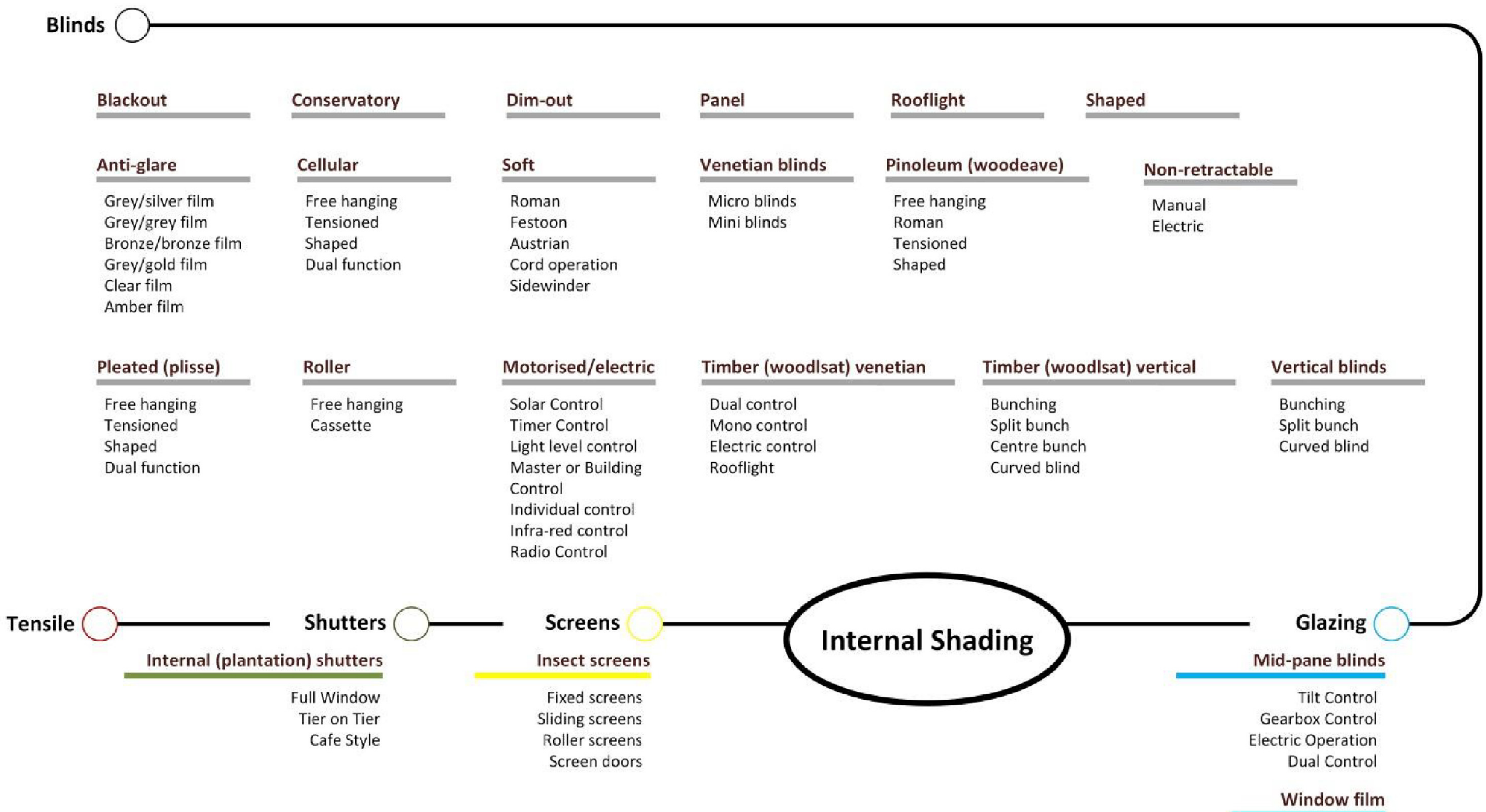

Figure 1. Product Dissemination of Internal Shading Products (Seguro and Palmer, 2016)

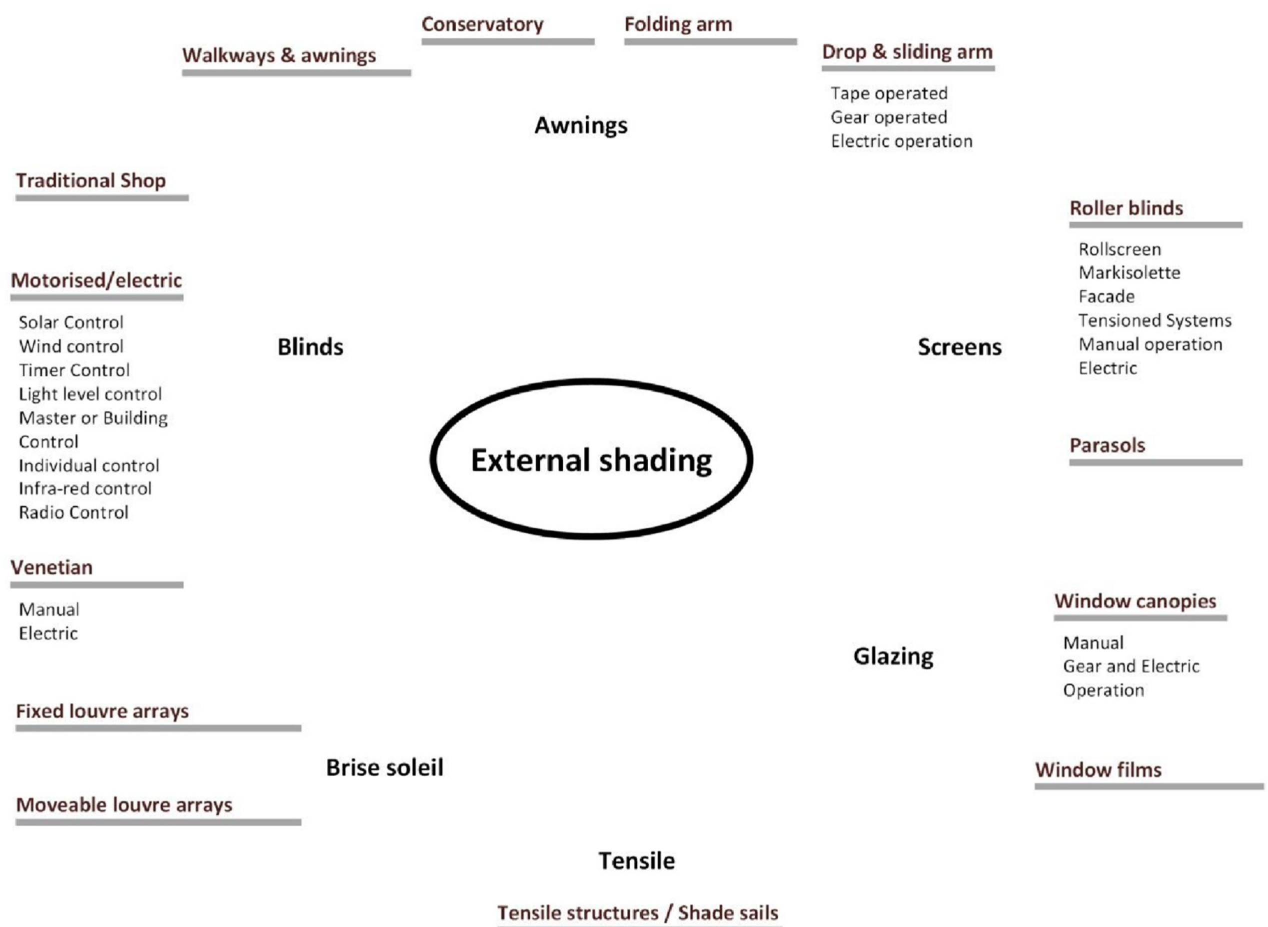

Figure 2. Product Dissemination of External Shading Products (Seguro and Palmer, 2016)

2.6.2 Product Performance Characteristics

2.6.2.1 Visual Properties

CIBSE (2015) recommends that when sunlight could cause discomfort or harm occupants, shading should be provided as a method of control. Fixed shading such as overhangs, brise soleil, louvres and screens or other redirection systems redistribute sunlight to improve lighting in internal spaces. However, fixed shading also reduces the amount of daylight and thermal solar gains admitted and therefore glazing areas may need to be increased or additional electric lighting may need to be supplied (CIBSE, 2015; Dubois, 2001). Moveable internal shading provides an effective means of control over glare which is frequently caused by low angle winter sun (Raynham, 2012).

When considering visual comfort, the Visible Light Transmittance (τ_v) of the blind material is the most important design parameter to consider. This takes into consideration the direct visual transmittance ($\tau_{v,n-n}$), which reflects the portion of illuminance that is transmitted directly through any holes or gaps in the curtain of the shading product, and the diffuse visual transmittance ($\tau_{v,n-dif}$), which reflects the portion of illuminance that is diffused and reflected by the curtain. The τ_v should be selected based on the requirements of the user, for bedrooms dim-out blind fabrics with a low τ_v are commonly selected to keep out unwanted light pollution (ES-SO, 2018b). The colour of a fabric or material can dramatically affect the τ_v (BBSA, 2015) as can the application of metallised coatings which are frequently used to improve the thermal properties of a shading fabric, these both affect the $\tau_{v,n-dif}$. Lighter colours increase the $\tau_{v,n-dif}$, whereas metallised coatings reduce the $\tau_{v,n-dif}$ (Mermet UK, 2018).

Even though a lighter coloured material can enhance the illumination of interiors by redirecting natural daylight deeper into the space they can also increase surface brightness and veiling reflections which can cause more frequent glare issues which is problematic for occupant visual comfort (BBSA, 2015; Dalke et al., 2004). Darker colours have lower τ_v properties and thus reduce veiling reflections and glare issues more effectively. Screen fabrics admit more light and have a higher τ_v as they have a higher $\tau_{v,n-n}$ and let more directly through the material in comparison to solid (dim-out) fabrics. Screen fabrics are often selected for offices or heavily glazed areas to allow more daylight into a space when shaded. Darker coloured screen fabrics offer the added benefit of providing a semi-transparent silhouette impression of a view out whilst preventing glare. Views to the outside are of great importance to user comfort and was found to be the reason of 52% of blind openings in a study conducted by Meerbeek et al. (2014). Often a balance is found between $\tau_{v,n-n}$ and the $\tau_{v,n-dif}$ and this is the reason why grey screen fabrics are commonly installed in offices. However, this will not necessarily eliminate glare issues as perceptions of glare discomfort are related to factors connected to the observer (such as age, culture, caffeine intake, genetic propensity of an individual to sleep), and the environmental context (position of a person within a room, interior surface reflections, orientation of the building, size of the glazing area and the position of the sun) among others (Pierson et al., 2017). BS EN 14501 (BSI, 2021b) gives guidance on shading product classifications for opacity and glare control, which is of importance when computers or visual screens are used. The standard also gives classifications for visual contact to the outdoors, night privacy, darkening and daylight utilisation.

2.6.2.2 Thermal Properties

CIBSE Environmental Design Guide (2015) recommends the use of shading to protect the indoor environment from direct solar radiation which can cause increases in ambient air temperature. This is supported by a substantial amount of academic research globally that identifies shading as key in reducing unwanted solar gain particularly in summer months (Alders, 2017; Curcija et al., 2013; Dubois, 1997; Larsen et al., 2012; Porritt et al., 2010; Tzempelikos et al., 2010).

Shading with a high solar reflectance (ρ_e) coupled with low solar transmittance (τ_e) and a low solar absorptance (α_e) are most effective in limiting solar gains passing through glazing as the total solar energy transmitted through the glazing is reduced (Hutchins, 2015). When glazing is combined with a shading device the total solar energy transmitted is termed the g_{tot} (BSI, 2017). However, shading with a high solar absorptance will increase in surface temperature and should be considered carefully when positioned internally as they may become a secondary source of thermal radiation (Hutchins, 2015). It is for these reasons that external shading is most effective at preventing solar gain as it prevents solar radiation entering the building and any radiation that is absorbed is emitted externally. The prevention of excess heat gains is beneficial in reducing active cooling loads. However, it is not always possible to install external shading products that run parallel to the window as windows in the UK traditionally open outwards. The installation of such shading products will prevent occupants from opening windows and using external vertical shading at the same time (Richard Partington Architects, 2012). Therefore, the installation of external shading products needs to be considered in the early design stage when the glazing system is specified.

Whilst reducing the g_{tot} is beneficial in summer months it has also been found to be useful in winter months. A real-world study conducted in winter in Montreal, Canada found that when a range of internal shading products were tested either fully closed (extended) or fully open (retracted) the internal shading maintained more comfortable internal operative temperatures (Bessoudo et al., 2010). The building tested was south-west facing, had a highly glazed façade with double low emissivity glazing. During the monitoring period the external air temperatures were between 0 - 15°C and on sunny winter days the solar radiation incident on the façade reached 800 W/m^2. When internal shading was extended the internal operative temperatures ranged between 18 - 26°C and when retracted ranged between 19 - 32°C. The range of temperatures experienced were significantly greater when the shading was retracted. This suggests that when shading products are extended, they reduce the fluctuations in increasing internal temperatures and help maintain lower internal temperatures overall. Currently there is limited evidence to suggest that overheating caused by solar gains is an issue in winter in the UK, although a study by Morgan et al. (2017) identified that winter overheating should be investigated further. Within the study new build Scottish homes were assessed for overheating whilst the homes were occupied. However, the testing methodology used meant that is was not possible to ascertain if the experience of overheating in winter was caused by a design issue (e.g., excessive solar gains, lack of ventilation or over insulation / air tightness) or an occupant behaviour (e.g., poor understanding or use of heating controls) as occupant behaviour was not monitored during the evaluation.

In addition to the thermal rejection properties shading products have, they are also beneficial in improving the thermal resistance of a façade. When extended they provide an additional layer to the glazing system and increase the thermal resistance (R-value) and reduce the thermal transmittance, termed the U-value, of the glazing system. This subsequently reduces heat loss through a building's façade reducing the heating load required to maintain comfortable internal temperatures (Hutchins, 2015). A study conducted by Glasgow Caledonian University (Baker, 2008) tested various shading systems in an environmental chamber to identify their U-values. When comparing the resultant U-values with that of the reference glazing in BS EN 14501 (BSI, 2021b) where a double clear glazing system has a U-value of 2.90 W/m^{2}K the following combinations of single glazing and shading had a better (lower) U-value performance:

- A honeycomb blind (with a metallised coating), U-value 2.4 W/m^{2}K
- Roller blind with a low emissivity coating, U-value 2.2 W/m^{2}K
- A timber shutter, U-value 2.2 W/m^{2}K
- Secondary glazing, U-value 1.7 W/m^{2}K
- Insulated timber shutters, U-value 1.6 W/m^{2}K
- Secondary glazing and curtains, U-value 1.3 W/m^{2}K

Furthermore, the combinations of single and secondary glazing and shading had either an equal or better U-value performance than double low emissivity glazing which has a U-value of 1.2 W/m²K (BSI, 2021b) :

- Secondary glazing and timber shutters, U-value 1.1 W/m²K
- Secondary glazing and insulated timber shutters, U-value 1.0 W/m²K

Opaque sash window roller blind (also known as a Victorian blind), heavy curtains and a free hanging roller blind were not as effective as they produced U-values of 3.2 W/m²K, 3.2 W/m²K and 3.0 W/m²K, respectively.

Seguro and Palmer (2016), also reviewed the impact of a variety of internal and external roller blind shading fabrics on the reference G and U-values of a variety of typical glazing systems. In all cases the shading reduced the G-value (g_{tot}) of the window system and the results were as follows:

- A single clear glazing[4] (G = 0.85) was reduced by 56% - 79%
- A double clear glazing system[4] (G = 0.76) was reduced by 16% - 82%
- A low emissivity glazing system[5] (G = 0.72) was reduced by 13% - 85%

In terms of U-values the following was found:

- A single clear glazing[4] (U-value, 5.80 W/m²K) was reduced by 26% to 57%
- A double clear glazing system[4] (U-value, 2.90 W/m²K) was reduced by 21% to 38%
- A double low emissivity glazing system[5] (U-value, 1.60 W/m²K) was reduced by 13% to 25%

The resulting g_{tot} and U-value varied depending on the shading fabric, position of the shading device (e.g., internal, or external) selected and the reference glazing they were combined with. This suggests that an understanding of the combined thermal properties of glazing and shading is crucial to the overall thermal performance of the glazing system.

On a clear summer's day, an unshaded window in the UK can admit 3 kWh/m^2 per day (Littlefair, 1999). For optimal energy efficiency it is important that this energy and its effects are managed appropriately. To achieve the g_{tot} and U-values described previously, blinds must be fully closed (ES-SO, 2018a). However, when shading products are partly open, they will still have a thermal impact on the glazed façade and the internal environment.

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[4] Reference glazing G and U-value were obtained from BS EN 14501 (BSI, 2021b)
[5] Reference glazing G and U-value were obtained from BS EN 13363 - 1 (BSI, 2007).

Guidance is not currently provided on methods for calculating solar transmittance for part open blinds (Hutchins, 2015) with the exception of venetian blinds which are calculated based on the tilt angle of the slats. Even though shading products may be beneficial for thermal comfort when extended this may subsequently create undesirable conditions for visual comfort, as the amount of daylight entering the building as well as the view will diminish. Therefore, a balance needs to be struck between the thermal and visual properties of shading products to meet the comfort needs of occupants.

2.6.2.3 Acoustic Properties

Acoustic Perceptions and Metrics

For any product to be considered beneficial for acoustic comfort it must be perceived by occupants to have a noticeable effect on the level of sound. Sound power level (SPL) is measured in decibels, dB, on a logarithmic scale. A 3 dB increase in sound power corresponds to the doubling of sound energy however the perception of this increase would be just perceptible to occupants whereas a 10 dB increase in SPL is perceived as twice as loud. Table 4 identifies the change in SPL and power required to achieve a change in perceived loudness (Goelzer et al., 2001).

Table 4. Subjective effect of changes in sound pressure level (SPL) (Goelzer et al., 2001)

Change in Sound Level (dB)	Change in power		Change in apparent loudness
	Decrease	Increase	
3	½	2	Just perceptible
5	1/3	3	Clearly noticeable
10	1/10	10	Half or twice as loud
20	1/100	100	Much quieter or louder

Identifiable audible sound varies in frequency between 20 Hz and 20 kHz but these ranges differ from person to person dependent on age. Speech occurs at frequencies between 125 Hz and 8,000 Hz although conventionally only the frequencies between 250 Hz and 5 kHz are examined (Peters et al., 2011). Audible frequencies of sound are split into octave bands where the upper frequency band of each octave band is double the lower band frequency. The central frequency of an octave band is referred to and identifies a specific octave band. For example, for the 250 Hz octave band the lower frequency band is 177 Hz and the upper band is 355 Hz but 250 Hz is referred to. Octave bands are further split into one-third octave bands which are used in the assessment of the acoustic environment as they provide a greater level of detail about the acoustic environment than evaluations of octave bands. For example, the 250 Hz octave band is split into three smaller one-third octave bands (200, 250 and 315 Hz) (Peters et al., 2011).

The A-weighting measurement (dBA) is the most common measure used within acoustic assessments as it correlates well with a wide range of human responses to real world noises and considers people's sensitivity to frequencies of sound between 1 and 4 kHz. Additionally, the A-weighting examines the majority of frequencies that speech occurs at, between 250 Hz and 5 kHz (Peters et al., 2011). The C-weighting (dBC) may also be measured as it better identifies lower frequencies of sound which are commonly experienced in buildings due to internal equipment noise (e.g., fans and mechanical ventilation systems), external traffic noise or impulse noises (e.g., sudden bangs and crashes) (CIBSE, 2015; Peters et al., 2011). Consequently, if a product or material can reduce internal sound levels by ≥ 3 dB over the A and/or C weighted frequencies a product can be considered to be having an acoustic impact on the building and a 'just perceptible' change in sound will be perceived by occupants. It is also important to note that whilst frequently occupant comfort is achieved by reducing SPLs in some cases too quiet a space can also cause discomfort. Acoustic comfort is very much dependent on the individual's preference for noise and/or the task they are undertaking (Clements-Croome, 2018; WGBC, 2014). However, in general complaints are usually made because there is too much sound being perceived within a space.

2.6.2.3.1 Transmission of Sound

The sound reduction index, R, of a building product identifies the sound insulation properties in dB for a specific frequency of sound and the weighted sound reduction index, R_w, provides the level of sound reduction over a specific range of frequencies. In general, the higher the R and R_w (the weighted sound reduction) the greater the sound level reduction and only a $R_w \geq 3$ dB will be perceptible to occupants (Goelzer et al., 2001). The testing method used to measure the R is specified in BS EN ISO 10140 (BSI, 2016). BS EN ISO 717 - 1 (BSI, 2013) provides a method of classifying the R values of building elements (such as walls, floors and glazing systems) into one single number quantity the R_w and provides a method for adapting the R_w for types of sounds that are commonly experienced in buildings. The singular R_w values means that products can be easily benchmarked against one another and considered within early acoustic design assessments. BS EN ISO 10140 (BSI, 2016) includes a test method for shutters which can also be applied to other shading products that are positioned vertical to the window. This test is intended to replicate a real-world scenario and thus few specifics are given regarding how the shading product should be installed and tested. Nevertheless, all the parameters selected should be detailed in the final test report with the resulting R_w of the shading product. Therefore, the R_w produced is specific to the glazing size and specification (e.g., single, double), shading product type tested (e.g., roller blind, vertical blind, venetian blind), mounting position (e.g., internal or external, within the window reveal or out of the window reveal), the mounting distances chosen, perimeter gaps (e.g., distance between the shading fabric and the window reveal) and the quality of the installation of the window within the partitioned wall.

Investigations into the impact of solar shading products on the transmission of sound are focused on the performance of external acoustic louvres (such as brise soleil) as it is well known that louvres reduce the transmission of sound of mechanical equipment (CIBSE, 2016). However, louvres have only been evidenced to mitigate higher frequencies of sound which is related to the width/thickness of the louvre and the angle it is set at (Viveiros et al., 2002). Higher frequencies of sound are generally easier to mitigate against where lower frequencies of sound are more problematic e.g., traffic noise. Additionally, a recent study found that metal louvres used in external venetian blinds can have a negative impact on internal acoustic conditions due to the refracted and diffracted sound fields imposed on the glazed façades (Martello et al., 2015). This study concluded that the material properties of the louvres need to be considered and more sound absorbing materials should be used. The REHVA Guidebook No12: Solar Shading - How to integrate Solar Shading in Sustainable Buildings (Wouter et al.,2010) acknowledges that the air gap between an external shutter and the glazing will also alter the level of sound transmitted into a building and it is stated that a 10 cm gap is most beneficial in reducing sound transmission. However, no justification for this specific distance was given within the literature.

Manufacturers of internal shading products frequently market their product for their ability to improve sound insulation. Considering some homes in the UK may be unable to upgrade windows to double glazed systems this benefit could be particularly useful in reducing noise ingress and improving occupant comfort in these types of buildings (Historic England, 2019). A study that identified the Weighted Sound Reduction Index, R_w, reviewed the impact of a variety of internal dim-out roller shading fabrics fitted within a frame and attached to the window opening and one external screen (semi-transparent) fabric. The shading products were tested in combination with two windows of differing sizes, 1 m^2 and 2 m^2 and the level of sound reduction was measured when the blind was opened (retracted) and closed (extended). The performance of the internal shading products varied depending on the weight of the fabric and the size of the window/blind being tested. On the larger window heavier fabrics 400 g/m^2 had a slightly better sound reduction performance, R_w 2 dB, than the lighter fabrics (300 g/m^2 and 350 g/m^2) which both achieved a R_w 1 dB. However, when the internal blind was tested with the smaller window there was no difference in R_w between the fabrics and all the fabrics achieved a R_w 1 dB. Yet, the inverse was found when the external screen fabric was tested. On the larger window there was no difference in the R_w but on the smaller window the R_w increased by 1 dB when the external blind was closed (extended). This study also identified that frequencies > 1,250 Hz were primarily affected by both shading system types. Overall, the shading products tested did not reduce the sound level by ≥ 3 dB and therefore did not reduce the SPL to an extent that would be perceptible by an occupant (Goelzer et al., 2001). However, several parameters were identified that could alter the resultant R_w performance of internal shading products, specifically the size of the window, the position of the blind relative to the window and the weight of the fabric.

More recently Catalina et al. (2019) carried out a study using a similar approach to the testing method within BS EN ISO 10140 (BSI, 2016). A sound source was emitted in one of two rooms, termed the source room, and the SPL in dBA was measured in both the source room and the receiving room. Different internal shading products were installed on an unspecified window in the partitioning wall of the two rooms. The internal blinds tested were a cellular cell (honeycomb) blind, an aluminium and PVC venetian blind, a bamboo blind, and a fabric roller blind with two layers of translucent & opaque striped fabric. The SPL was measured in five places within the receiving room and the averaged result found the cellular cell blinds were most effective in improving the sound insulation of the room. The next best was the fabric roller blind, followed by the aluminium venetian blind, the bamboo blind and the worst performing blind was the PVC venetian blind. The cellular blind in combination with the window and partitioned wall achieved a sound reduction of 18.1 dBA where the PVC venetian blind achieved a sound reduction of 17.4 dBA. Overall, the cellular blind was the best shading product at reducing the transmission of sound. Cellular blinds incorporate an air gap within the fabric structure (see Figure 3) similar to glazing units and it is this gap within glazing units that contributes to their ability to prevent sound transmitting through them (Garg et al., 2012). Therefore, it is this design feature in the design of cellular blinds that contributes to their acoustic transmission performance.

Figure 3. Cellular / Honeycomb Blind (BBSA, 2020).

Unfortunately within the study conducted by Catalina et al. (2019) no measurement was taken within the receiving room when no shading product was installed at the window, making it impossible to identify how the internal shading products tested affected the sound insulation properties of the window. Nevertheless, differences were identified between the sound insulation performance of the differing internal shading products tested. However, these differences were < 3 dB suggesting that an occupant would be unable to identify an audible difference between the type of blind installed.

Some manufacturers claim their shading products are more beneficial in reducing sound transmission however, no data has been found where the R or R_w performance can be easily compared between differing shading fabrics or systems. Even though BS EN ISO 10140 (BSI, 2016) and BS EN ISO 717 - 1 (BSI, 2013) provide a testing method and a classification method to categorise the performance of shading products these are not widely adopted by the shading industry. The shading industry produces a wide range of shading products where differing fabrics can be used across products and installed in differing mounting positions in combination with varying sizes and specification of glazing. Therefore, the limitations of the test method mean that testing every scenario would come at a significant cost to manufacturers of shading products. A further barrier is that any additional sound insulation benefit provided by a shading product will only be achievable when occupants close (extend) them. Additionally, how shading products are installed, and the shading system options available are limited by the building design. Futhermore, in most installations the position of the curtain of the shading products varies (i.e., extended or retracted) depending on the thermal and visual comfort perceptions of an occupant. It is therefore likely that because of this, and the absence of research that identifies shading products can improve the sound insulation of windows by ≥ 3 dB that there is a lack of incentive within the shading industry to invest in testing their products to identify their acoustic properties.

2.6.2.3.2 Absorption of Sound

Fabrics used internally can reduce the reverberation time (RT) of sound within a room by providing additional acoustic absorption. This reduces the amount of sound reflected off hard surfaces in a space, such as glazing (Seguro and Palmer, 2016). The RT is the amount of time in seconds (s) taken for sound to decay after a sound source has stopped. The RT of a room is proportional to the volume of a room and inversely proportional to the amount and type of absorptive materials within a space. Therefore, the RT of a room can be estimated if the overall size of the room, the absorptive properties and size of the absorptive materials in the room are known (BSI, 2014).

The ideal RT of a room depends on the type of sound occurring within a space. Longer RTs are recommended for music as it is not necessary to hear each individual sound produced (e.g., each note played by an orchestra) and they help blend musical sounds, covering discrepancies in synchronism or intonation, and increase the overall loudness and richness of music (Zeman et al., 2010). For speech, the RT within a room must not be too long or the sound level of one syllable of a word will not have decayed before the sound of the next syllable within a word is heard, making the clarity of the speech poor. For example, the RT in churches tends to be significantly longer than most building types due to the traditional hard finishes and volume of these types of buildings which is why speakers in large rooms need to speak slower to be understood by those listening. The RT in large churches can be more than 4 s where in most standard offices (that have an absorbent ceiling and carpeting on the floor) the RT will be approximately 0.5 s. Low RTs in open plan offices also prevent office workers being disturbed by sound transmitting from colleagues conversations at other workstations within the same office (Fry, 1988), providing speech privacy.

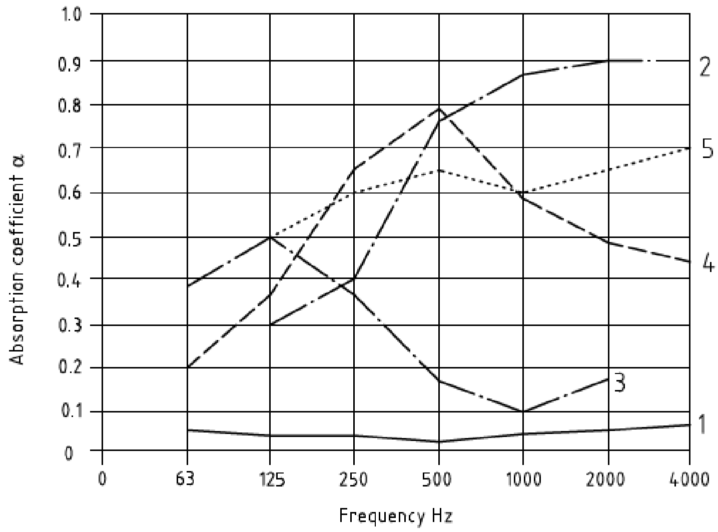
The sound absorption properties of a material or product are defined by the Sound Absorption Coefficient, α_s. This is the ratio of absorbed sound energy to incident sound energy, where 1 identifies a perfect absorber and 0 offers no sound absorption. BS EN ISO 354 (BSI, 2003b) provides a methodology for measuring the absorptive properties of a 'curtain, drapery, window shade or window blind' by testing a ≤ $10m^2$ sample installed in a reverberation chamber. The time taken for sound to decay across one-third octave band frequencies with and without a test specimen in a reverberation chamber (a room with a known reverberation time) are compared, allowing the acoustic absorption provided by the material (or product) to be quantified for each one-third octave band. From this data and additional data collected relating to the testing conditions (e.g., air temperature and the volume of the reverberation chamber) and fixed values (e.g., the propagation of speed of sound and the power attenuation coefficient) the α_s can be determined. Subsequently, BS EN ISO 11654 (BSI, 1997b) can be used to simplify and classify the α_s for each one-third octave band frequency into a Practical Absorption Coefficient (α_{pi}) for each octave band. These values are then used to calculate the Weighted Absorption Coefficient (α_w) summarising the performance across all octave bands. Lastly an ISO Class can be determined based on a A - E scale where an A class absorber is optimum at reducing reverberant sound. This can be used to compare the sound reduction performance of materials (or products) used within a space.

Within architecture it is widely acknowledged that fixed tensile structures can be beneficial in improving acoustic absorption in heavily glazed or large open spaces. The structures shown in Figure 4 are created out of 'flat' fabrics structures and the same flat fabrics are also used in more conventional shading products (e.g., roller blinds) (Mermet, 2017).

Figure 4. (Left) Conservatory Sails (Inshade, no date), (Right) Tensile Structure (tensARC, 2015).

There is a lack of research conducted on the sound absorption properties of shading fabrics and shading products used in homes and offices. In the study carried out by Catalina et al. (2019) who quantified the sound insulation properties of various internal blinds (discussed in Section 2.6.2.3.1, p. 25) the researchers also assessed how the shading products tested affected the RT of a room. The products tested were a cellular cell blind, an aluminium and PVC venetian blind, a bamboo blind, and a fabric roller blind. The RT of one-third octave bands between 63 Hz and 8 kHz were measured and the research concluded that the internal shading products tested performed relatively similarly at mid (1 kHz) and high frequencies (8 kHz). At mid-frequencies, the bamboo blind decayed sound the slowest and had a RT of 4.8 s, followed by the PVC and aluminium venetian blinds (RT = 4.7 s) and the roller and cellular cell blind decayed sound the quickest at 4.4 s. At higher frequencies all the blinds except for the roller blind had a RT of 1.0 s where the roller blind had a slightly quicker RT of 0.9 s. There were greater differences in RT when low-frequency sound (63 Hz) was assessed. The PVC and aluminium blind were the least effective in absorbing sound and had a RT of 8.6 and 8.4 s respectively, followed by the cellular cell blind and the roller blind with a RT of 8.2 and 8.1 s, respectively. The bamboo blind performed the best and achieved a RT of 7.8 s. Considering the study also found that the cellular blind was most effective at providing sound insulation and had a generally good performance across all frequency bands (low, middle, and high) in reducing the RT Catalina et al. (2019) concludes that cellular blinds are the best option for attenuating sound overall. Unfortunately, it was not stated what the RT of the room was without any shading product installed to the window was so the benefit shading products provided to the room overall cannot be determined.

More conventional types of acoustic absorbers that are specifically designed to reduce the RT within rooms include porous, panel and cavity absorbers. Porous absorbers provide a high level of sound attenuation over a broad range of frequencies, although they are more effective over mid and high frequencies. Panel absorbers provide a low level of sound attenuation over a broad range of frequencies and are more effective against low and mid frequencies and cavity absorbers provide a greater level of attenuation but over a narrow range of specific frequencies. Figure 5 from BS 8233 (BSI, 2014) provides typical acoustic absorption coefficients for these types of absorbers and a typical hard finished wall.



1		Hard finish: Plaster on solid backing
2		Porous absorber: 50 mm mineral fibre 50 kg/m³ Performance is not significantly affected if protected by a perforated panel with at least 30% open area
3		Panel absorber: 9 mm ply, 50 mm cavity containing 25 mm mineral fibre
4		Perforated panel: 14% perforations, 25 mm cavity containing mineral fibre
5		Perforated gypsum ceiling tile/board: 13 mm gypsum tile/board, 16% perforations, suspended with 200 mm plenum

Figure 5. Typical Acoustic Coeffcients for (1) Hard Finish, (2) Porous Absorber, (3) Panel Absorber, (4) Perforated / Cavity Absorber and (5) Perforated Ceiling Tile (BSI, 2014).

Parallels can be drawn between the acoustic performance of porous acoustic absorbers and internal shading products as both utilise fabric, vary in shape and form and are more beneficial in reducing RTs across mid and high frequencies. We can therefore assume that shading fabrics with denser weaves and more surface area will provide better acoustic absorption and transmission properties (Peters et al., 2011). This also supports why cellular blinds were most effective in the work of Catalina et al. (2019) as cellular blinds have a larger fabric surface area because of the dual layer and concertina design needed to create the structured shape.

The installation and use of fabrics in different shading products (e.g., roller blinds, vertical blinds, honeycomb blinds) is considered in the testing standard BS EN ISO 354 (BSI, 2003b). However, no research has determined the extent that vertical shading products can absorb sound or identified how the installation affects the acoustic absorption. The installation distance of shading products varies depending on the specific design of the building and the type of shading product being installed. For certain shading products the installation distance is critical to the function of the shading product (e.g., shading products that fit within a frame), but other shading products are more versatile (e.g., roller blinds) as they can be installed either within the window reveal or outside the window reveal.

2.6.2.4 Control Strategies

Shading products can be operated using manual, motorised, and automated control strategies. Economical drivers have encouraged the development of blinds and shutters with the integration of motorisation and automated systems. Motorised systems are considered those that operate (open or close) based on a manual input, such as the push of a button or operation of a switch. Automated systems can vary widely in terms of how they operate. Some of the more simplistic systems link to a timer, a wind sensor (for external systems only) and frequently offer the ability to be controlled by various mobile technology platforms (e.g., mobile phones, tablets). Whilst other systems are more complex and link to internal and/or external lux sensors, air temperature and/or pyranometer (which measure solar radiation) sensors. Each manufacturer then supplies a control box which applies an algorithm that dictates which measures to consider that will instigate a blind movement. However, with all automated systems it is recommended that a manual override system is provided so occupants can override any unwanted movements (BBSA, 2016; BRE, 2017a).

The biggest barrier to the energy saving potential of shading products is the lack of occupant interaction and use of blinds. In a longitudinal office study carried out by Paule et al. (2015) it was observed that manual shading systems were rarely used (1.42 movements per week) and motorised blinds were operated more frequently. Blind movements increased by 18% when motorised. A further study conducted in France found that motorised venetian blinds were used three times more than manual fabric blinds (Sutter et al., 2006). Whilst motorised shading products may enable more users to operate them, the motivations behind occupants opening or closing blinds are often unclear and therefore control strategies for automated systems vary.

Most of the research that has investigated the motivations behind occupants operating blinds have been conducted in offices. In this research blind movements were related to the following aspects (BRE, 2017a; Meerbeek et al., 2014; O'Brien et al., 2013; Van Den Wymelenberg, 2012):

- External/internal environment conditions (e.g., glare issues, daylight utilisation, or thermal preference)
- Preference for views out of a window
- Time of day
- Occupancy
- Façade orientation
- Privacy

Very few studies have been conducted in residential properties. A detailed study carried out in Canada found that there were similar motivations for blind movements as there are in offices. Residential blind movements were concluded to occur less frequently than in offices, however within the study occupants were not interviewed or surveyed so psychological behaviours and differences in occupancy patterns may have skewed the results. For example, the research team were unable to determine when occupants were at home or at work or if they were on holiday (Bennet et al., 2014). Perceptions of security and habitual routines have also been found to influence motivations (GHA, 2014). Therefore, there are both physiological and psychological reasons for operating blinds. Research literature tends to agree that the most significant measure in motivating internal blind use is related to visual comfort (BRE, 2017a; O'Brien et al., 2013; Van Den Wymelenberg, 2012). However, increases in air temperature have also been found to correlate with internal blind movement but this relationship is often weaker than visual comfort measures. This is believed to be because solar gain does not affect an occupant instantaneously, particularly in offices where active cooling is used. A study cited by O'Brien et al. (2013) that compared blind movements in both naturally ventilated and air conditioned offices observed that blinds were operated 19% more frequently in naturally ventilated buildings. Furthermore, within the UK it has been acknowledged that culturally we are unaware of how to protect ourselves from warmer weather conditions which may also contribute to why shading is infrequently opened and closed in relation to internal temperatures (CCC, 2016).

The studies conducted on automation are limited due to the complexities of analysis and further research is required to identify the best way of integrating these systems without negatively affecting occupants. A Dutch survey carried out on 600 residential occupants found that users were not accepting of the prospect of integrating automatic solar shading.

Nearly 50% preferred a manual control strategy as opposed to automated control and almost 20% said they would consider a combination of automation and manual systems (Frontczak, 2012). Automatic control of shading products has to be appropriately specified and maintained to be successful in providing occupant comfort (Foldbjerg et al., 2020). Implementing strategies so movements occur during work breaks, override functions built in for a set period of time (Littlefair et al., 2010), graduation of blind movements, and providing occupants feedback as to why movements are being made have all been proven to enhance user satisfaction (Frontczak, 2012; Meerbeek et al., 2016). In order to satisfy various users each room requires tailoring to the occupants' needs which raises new challenges for the industry (BRE, 2017b). Maintenance and commissioning of control systems after installation is now essential to ensure that systems are working to the benefit of users whilst simultaneously improving energy savings (Attia, 2019; Selkowitz et al., 2003).

2.6.3 UK Building Regulations and Voluntary Building Certificates

Shading is not specifically prescribed in Building Regulation Part L1A and L2A (HM Government, 2010, 2010b) although Schedule 1 L1(a)(i) does state that "reasonable provision shall be made for the conservation of fuel and power in buildings by limiting heat gains and losses". Both documents (Part L1A and L2A) provide guidance on how this can be achieved. In Part L1A (which addresses new homes), Criterion 3 recommends the incorporation of shading as well as the appropriate window size and orientation, ventilation and thermal mass can limit solar gains. Compliance with the regulation can then be checked by following the Standard Assessment Procedure (SAP) which assesses the energy performance of domestic buildings (BRE and DECC, 2014).

BRE and DECC (2013) have evidenced SAPs inaccuracy in predicting overheating risk. Buildings that were found to be at a 'Medium' risk of overheating through SAP Appendix P were reported to be having "difficulty keeping one or more rooms cool during the summer months". In this version of SAP (2012 version 9.92) Appendix P provides an overheating assessment where a rating of 'Medium' or lower should be achieved to ensure a building does not overheat in summer months (June - August). This calculation is separate from the calculations related to the building's energy efficiency or CO_2 emissions. SAP Appendix P (BRE and DECC, 2014) provides a calculation methodology which identifies the predicted internal temperature of a dwelling in summer months and the rating relates to a temperature threshold that should not be exceeded in any month. To achieve a 'Medium' rating an internal temperature of ≥ 22°C and < 23.5°C can be considered at medium risk from overheating and a temperature ≥ 20.5°C and < 22.0°C can be considered at slight risk.

Temperatures that are ≥ 23.5°C and are below 20.5 are considered at high and low risk, respectively. The calculation for each month considers various factors that contribute to overheating in buildings. These include the amount of solar gain, ventilation, the thermal capacity of the building and the external mean summer temperature in specific regions in the UK. The amount of solar gain admitted through the glazed area on each facade is considered by adjusting the monthly mean global solar irradiance (W/m^2) received on a horizontal plane for various regions within the UK. It is adjusted by the monthly mean solar declination angle, the latitude, orientation and tilt of the receiving facade, the total solar energy transmittance of the glazing and the presence of shading and shading products. Overhangs, buildings that overshade the dwelling and internal and external shading products (including net curtains and curtains) can be included within the calculation methodology if their presence is known. For shading products, the recommendation is to assume dark curtains are installed and products are assumed to be closed during daylight hours in the summer months being evaluated. The performance of shading products are factored into the calculation methodology by a 'Zblind' value. However, how the 'Zblind' values relate to the thermal characteristics of shading products is not explained within the methodology and no reference is given to any existing BS EN standards used by manufacturers of shading products to identify and benchmark the thermal characteristics of differing shading products e.g., BS EN 14501 (BSI, 2021a).

Even though the Appendix P calculation considers many variables that affect the level of solar gain received the baseline data used is average monthly climate data. This means that the calculation cannot accurately account for the variability in the amount of solar radiation received by buildings and the changing solar angles throughout the year. The assessment also only considers summer months (June - August) where there is a greater chance of excessive solar gain penetrating buildings in mid-season months due to the lower altitude of the sun. There is little clarity in how the performance characteristics of shading products are evaluated so designers, manufactures and specifiers of shading products cannot identify how real products relate to the design requirement to prevent buildings from overheating. The assumption that all shading products will be closed in summer months may also be an inaccurate assumption as the motivation for opening and closing shading products is often determined by other factors (e.g., visual comfort) and so some shading products are likely to be open (retracted) in summer months to provide views out or allow daylight in.

Within Part L2A (HM Government, 2010b), which addresses buildings other than dwellings, recommendations are given regarding window size, orientation, and the G-value of the glazing system. This legislation was altered from the 2006 edition which previously required the number of hours of overheating to be assessed (when occupied) and recommended an internal solar gain limit of 35 W/m^2 on peak summer days. It has been suggested that the removal of the 2006 criteria has weakened the regulatory document (CIBSE, 2018; House of Commons Environmental Audit Committee, 2018).

The inclusion of shading is encouraged in new building design within the 'The Cooling Hierarchy' in The London Plan, Policy 5.9 (Greater London Authority, 2016) and within the Good Homes Alliance (GHA) Overheating in New Homes Tool and Guidance Document (GHA, 2019). The latter is a voluntary tool aimed to be used by local planning authorities and early-stage building designers where the integration of shading in the building design offers the most points in relation to overheating mitigation and the former are compulsory requirements for any new building within the Greater London Authority.

Within BREEAM New Construction for non-domestic buildings shading is considered as a preventative measure for glare (HEA 01, Visual Comfort). One credit is awarded although this is an optional credit (BRE Global Ltd, 2014). Within the BRE Home Quality Mark (HQM) a statutory credit is required for 'Active Systems' to be in installed, working and ready for use. External shading is considered an optional 'Active System' to be installed for temperature control. Furthermore, the HQM has a minimum requirement for temperature control and this requires a thermal analysis to be carried out using either the HQM SAP XML or the CIBSE TM59 Methodology (CIBSE, 2017). This thermal analysis then needs to be provided to occupants with instruction of how to best operate their homes to achieve good thermal comfort (BRE, 2018).

Lastly within the UK solar shading products are categorised by the National Building Specification as a 'General fixture/furnishings/equipment' element and are therefore not seen as an integral part of the building services package in the UK (RIBA, 2019; Seguro and Palmer, 2016).

2.6.4 Energy Savings

The performance characteristics of shading products have been previously evidenced to have a subsequent effect on the cooling and heating loads and the electric lighting requirement of a building when used. There are relatively few studies globally that have investigated the energy savings provided by shading products alone (Dubois, 1998, 2001; Hutchins, 2015; PHYSIBEL, 2005; Seguro and Palmer, 2016; Wouter et al., 2010). There are even fewer studies that have evaluated the energy savings provided through the use of shading products in the UK (Seguro and Palmer, 2016). Therefore, this section aims to describe the extent of the energy savings that shading products have been previously identified to provide and this review has been broadened to consider studies carried out in Europe as well as the UK. The outcomes and parameters investigated in these studies are summarised in Table 5 (p.44) and the preceding section discusses the approaches and outcomes in further detail.

A UK based study carried out by the National Energy Foundation (Seguro and Palmer, 2016) simulated the energy required within an office building in London. The office building was south facing, heavily glazed with a glazing to wall ratio (GWR) of 80% and had double low emissivity glazing. The base case had no shading installed and the results of the base case were compared with simulations that incorporated two types of internal screen roller blinds and two types of external venetian blinds. The author commented that the shading products included in the simulation were not particularly high performing in terms of their heat rejection or heat insulation properties and highlighted that the results of the simulation are sensitive to the climate file and the assumptions used within the model. The base case space heating demand was 17 kWh/m^2. yr, the cooling demand was 109.6 kWh/m^2. yr and the total end use energy was 207.4 kWh/m^2. yr. The lighting energy costs were the same in all modelling simulations as the lighting and equipment schedule remained the same in all simulations. The control strategy for shading in this study meant that the shading product would extend (close) when the solar radiation incident to the glazing exceeded 400 W/m^2. Table 5 on p.44 identifies that in all four shading scenarios the cooling demand of the building reduced by between 10 - 71% depending on the shading type, and the heating demand increased by between 9 and 77%. However, the total end use energy reduced by between 6 and 40% with external shading products saving more energy than internal shading products overall. The increase in heating loads as a result of including shading suggests that when shading was extended in the heating season it prevented valuable solar gains entering the building which contributed to an increase in heating loads. Similar findings were reported by Dubois (1997) who summarized a large body of literature across Europe and America regarding the energy impact of shading products. This concluded that external shading products could reduce the cooling loads of a building but may consequently increase heating loads as useful solar gains are lost when shading products are extended. Dubois (1997) also suggested that the optimal solar shading strategy varies depending on the climate and in heating dominated climates (like the UK) shading systems that are either; removeable (i.e., can be retracted) in winter or are fixed with medium to high solar transmittance and a high thermal resistance are more energy efficient.

To further research in this area Dubois (1998) carried out a parametric study that used a building simulation tool to identify how energy savings of shading products altered when differing user behaviour strategies of an external awning were implemented. In the study comparisons were made between the heating and cooling energy use of a building without an awning (the base case) and the energy use of a building with an awning. Three user behaviour strategies of an awning were simulated as well as three orientations (north, east and south) of the glazed area of the building. The awning was either permanently extended throughout the year (in a 'fixed' position), extended only in summer (termed the 'seasonal' awning) or a 'dynamic' opening and closing strategy was assumed. The 'dynamic' behaviour assumed that the awning would extend only when cooling was active and retract when heating was active. The building simulated had a GWR of 30% and included double clear glazing. When the base case building was orientated south, the annual energy use for heating and cooling was approximately 100 kWh/m^2. yr, ≈ 23 kWh/m^2. yr was required for cooling and ≈ 77 kWh/m^2. yr was required for heating. The energy savings of each shading control strategy and for each orientation are tabulated in Table 5 as a percentage of the base case (without shading scenario) and these show that the 'dynamic' model provided the greatest annual energy use saving of 20% when orientated south. The heating energy required remained the same as the base case however the cooling energy reduced by ≈ 83%. This suggests that to obtain the optimum amount of energy the strategy needs to alter depending on whether heating or cooling is in use, and thus movements should be also dependent on internal temperatures. Interestingly, this study found that when the 'dynamic' strategy was implemented on the north façade there was still an energy saving when shading was included, although the saving was much smaller than the savings obtained on the east and south façade. This is interesting because generally shading is considered not needed on north orientated glazed areas as relatively little direct solar gain is admitted. However, Dubois (1998) attributed this to the shading reducing the diffuse solar radiation reaching the window.

Wouter et al. (2010) carried out a simulation study that forms part of REHVA Guidebook No12: Solar Shading which identifies the lighting, heating, cooling, and primary annual energy use of an office in Stockholm, Amsterdam, and Madrid with and without external venetian blinds. The simulated office had a GWR of 60% and three types of glazing were assessed (double clear, double low emissivity and solar control glazing). The study compared the amount of primary energy required between a building with and without an external venetian blind. The control strategy for extending the blind differed depending on the climate. In the colder climates, Stockholm and Amsterdam, shading products were only extended in summer months when the internal air temperature exceeded 22°C and the solar irradiance on the window exceeded 200 W/m^2. The control strategy for Madrid was the same except there was no seasonal restriction (i.e., they could open and close all year round). Additionally, in this study all glazing orientations were assessed. When the base case (without shading scenario) was compared to the with shading scenario for all climates, glazing types and orientations the inclusion of external shading meant that the primary energy use either stayed the same or provided an energy saving. In Stockholm when external shading was installed on the north facade there was no primary energy saving but for all other orientations the primary energy use reduced. This may be because the threshold of 200 W/m^2 on the north façade meant the shading device never extended as the amount of solar radiation received on the north face of a building is significantly less than on all other orientations. Wouter et al. (2010) provided similar conclusions to the work carried out by Dubois (1998) in Stockholm which identified that cooling energy use reduced significantly whilst there were slight increases in heating (and additionally lighting energy use) when external shading was incorporated into the design. In the warmest climate, Madrid, the percentage of cooling energy savings were greater when shading was included because of the larger requirement for cooling. The details of this study have not been included within Table 5 as the base case (without shading) energy use was not identified within the publication.

The work of Seguro and Palmer (2016), Dubois (1998) and Wouter et al., (2010) used energy simulation tools to provide quantifiable evidence that shading products can save energy. However, these studies are only representative and specific to the various modelling parameters input in the simulations and the climatic conditions within the weather files used. Further studies have been carried out that try to predict the amount of energy and CO_2 emissions that could be saved if shading products were installed on all residential and commercial buildings across Europe. The first of these studies was commissioned by the European Solar Shading Organisation (ES-SO) who represent several shading industry organisations across Europe and was carried out by PHYSIBEL (2005). The study uses building energy performance simulations across four regions in Europe to estimate the energy and carbon emission savings if shading was installed and used effectively on all buildings within the EU25. The initial simulations carried out considered a range of parameters that could potentially impact the energy saving impact of shading products. The study considered:

- Two shading system types - a roller blind and a roller shutter;
- Two shading system positions - internal and external;

- Two orientations of a façade - NE and SW;
- Two types of building - one representative of an apartment building and the other of an office both with GWR of 30%;
- Two thermal occupancy profiles - one representative of an office and the other residential premises;
- Two window types - double glazing (U-value = 2.6 W/m^2K) and double low emissivity glazing (U-value = 1.8 W/m^2K);
- Four climates; Brussels (west), Budapest (east), Rome (south) and Stockholm (north) each of which were representative of the four climate regions across Europe.

A total of 256 sets of simulations were identified as possible to produce from the number of variables considered that could potentially influence the energy consumption of a building. Of these 256 sets, 24 sets of simulations (with and without shading) were carried out which were believed to identify the extent of the impact shading could have on the cooling and heating demand. In 4 of the 24 simulations that included shading, the heating demand increased when compared to the 'without shading' base case and in all 24 with shading simulations the cooling demand reduced. In the four cases where heating energy consumption increased, it increased by < 10% equating to < 1 kWh/m^2. yr in heating demand when compared with the 'without shading' scenario. The increases were relatively small and in all cases the energy penalty was offset by the cooling demand energy savings. In the remaining 20 cases where the heating demand reduced through the inclusion of shading, savings of 3 - 17% were obtained equating to a 1 - 14 kWh/m^2. yr heating demand saving. The cooling demand reduced by 16 - 97% across the 24 sets of simulations equating to a 2 - 41 kWh/m^2. yr reduction in cooling demand. It was also observed that in half of the 24 cases, the total cooling demand was reduced to < 200 kWh/year which could potentially mean that active cooling would not necessarily need to be installed. Table 5 identifies the range of energy consumed in the 'without shading' base case and the average energy saved across the models for each climate.

Following the evaluation of the 24 cases a 'Feasible Energy Demand Reduction (FEDR)' for both cooling and heating in kWh/m^2. yr for the four climates considered was calculated. The FEDR for western European climates was concluded to be a reduction of 10% in heating demand and 15% in cooling demand. A reduction of 10% in heating and 30% in cooling in eastern climates, a reduction of 5% in heating and 30% in cooling in southern climates and lastly a 15% reduction in heating demand and 20% in cooling demand in northern climates.

The FEDR were then extrapolated across all residential and office buildings in Europe to calculate a 'Feasible Heating and Cooling CO_2 Emission Reduction' and a 'Feasible Heating and Cooling Mtoe Reduction'. This was done by calculating the total applicable floor area (the number of habitants in each region multiplied by the floor area per habitant and a 'Blind or Shutter Application Factor' of 0.5[6]) and the 'Feasible Fuel Equivalent Energy Demand Reduction' (the heating and cooling demand reductions divided by an assumed system efficiency)[7]. The 'Feasible Fuel Equivalent Energy Demand Reduction' was multiplied by the average CO_2 emission factor and the total applicable floor area, to provide the 'Feasible CO_2 Heating and Cooling Emission Reduction'. The product of the 'Feasible Fuel Equivalent Energy Demand Reduction' was also multiplied by the applicable floor area and divided by a Mtoe to MWh conversion factor (1.16×10^7) to provide the 'Feasible Heating and Cooling Mtoe Reduction'. The results of this extrapolation found that if solar shading products were installed across Europe there would be a CO_2 emission saving of 31 metric tonnes per annum through heating energy demand reduction and a further 80 metric tonnes per annum would be saved through cooling energy demand reductions. The 'Feasible Heating and Cooling Mtoe Reduction' identified a saving of 12 Mtoe per annum in cooling energy demand and 31 Mtoe per annum in heating energy demand reductions if solar shading products were installed across Europe based on the assumptions made in the study.

Hutchins, (2015a) furthered this research by taking into consideration the type of glazing already installed across the EU-28 and the total end-use energy consumption figures published for commercial and residential buildings in 2014 which equated to 438 Mtoe. In 2011 a paper published by TNO and Glass for Europe identified the type of glazing installed in residential and commercial properties across Europe. It suggested that single glazing is installed in 44% of properties, clear double glazing is installed in 42% of properties and 14% have double low emissivity glazing installed. The method used to evaluate the mean percentage of heating and cooling demand savings differed by combining 4 types of internal and external shading with three differing types of glazing (single, double clear and low emissivity double glazing) but used the same four climates assessed by PHYSIBEL (2005). The four combinations internal and external shading considered 4 U and g_{tot} thermal performance values to identify the 'highest' and 'lowest' energy saving

[6] The 'Blind and Shutter Application Factor' considers that in some properties across Europe shading is either; already installed, not required (for example if a building is externally shaded by other buildings or vegetation) or when buildings are not effectively (or are weakly) heated or cooled.
[7] For heating a system efficiency of 0.8 was used. For cooling a system efficiency of 0.71 based on COP =2 and an electricity to fuel conversion of 2.8.

performance for shading which were used to calculate the mean performance. In contrast to the other studies described, a 'day' and 'night-time' control strategy was simulated. At night-time shading products were assumed closed to improve heat retention at night and in the day a dynamic strategy based on the incident solar radiation on the outside of windows was assumed including a 'part-open' scenario. In the day shading products closed when > 400 W/m^2 and were opened when < 200 W/m^2 was received. They were then simulated to be 'part-open' when the incident solar radiation received was between 200 and 400 W/m^2. Similarly, the energy savings identified were compared with a 'without shading' scenario and when compared shading products were identified to save a mean of 25% and 46% in heating and cooling energy when single glazing was installed across all 4 climates. A mean of 15% in heating and 38% in cooling demand when double glazing was installed and a mean of 8% in heating and 30% in cooling demand when double low-e glazing was installed. The savings were higher than those found by PHYSIBEL (2005) because a broader range of shading product performances' were investigated.

To extrapolate the mean percentage of energy savings for the 4 climates across the EU-28 building stock it was assumed that:

- 60% of the 438 Mtoe of end-use energy for commercial and residential buildings was used for space heating and cooling, equating to 263 Mtoe.
- Two splits of end-use energy were considered a 50:50 split between heating and cooling and a 70:30 split.
- A 'Blind and Shutter Application Factor' was considered which was 0.75 (25% higher than what was assumed in the PHYSIBEL, (2005) study (see Footnote 7).

Based on the 70:30 split of end use energy split for heating (184 Mtoe) and cooling (79 Mtoe) and the aforementioned assumptions it was found that the installation of shading products could reduce the energy consumption for heating by 25 Mtoe (14%) and cooling by 24 Mtoe (30%), resulting in a total end-use energy saving of 49 Mtoe (19%). These mean energy savings percentages are also included within Table 5.

Table 5. Energy savings provided by shading products.

Author	Location	Building Typology	Glazing Type	Orientation	Base Case (without shading) Cooling Load	Base Case (without shading) Heating Load	Base Case (without shading) Total Energy	Shading Type	Shading Variant (with shading) Cooling Load (% per year*)	Shading Variant (with shading) Heating Load (% per year*)	Shading Variant (with shading) Total Energy (% per year*)
Seguro and Palmer, (2016)	London, UK	Office	Double Low E Glazing U = 1.2 W/m²K, G = 0.59	South	109.6 kWh/m²yr	17 kWh/m²yr	207.4[a] kWh/m²yr	Internal Roller Blinds	-21%	15%	-12%[a]
									-10%	9%	-5%[a]
								External Venetian Blinds	-77%	71%	-40%[a]
									-63%	59%	-37%[a]
PHYSIBEL, (2005) ES-SO, (2006)	Brussels, Belgium	Office and Residential Average	Average of Double Glazing, U = 2.6 W/m²K, G = 0.63, and Double Low E Glazing U = 1.8 W/m²K, G = 0.63.	Average of SW & NE	61 - 603 kWh per year	726 – 2535 kWh per year	-	External Shutter & Internal Roller Blind	-15%[b]	-10%[b]	-
	Budapest, Hungary				1244 - 1259 kWh per year	2406 - 2428 kWh per year	-		-30%[b]	-10%[b]	-
	Stockholm, Sweden				303 - 704 kWh per year	1126 - 3854 kWh per year	-		-20%[b]	-15%[b]	-
	Rome, Italy				889 - 1663 kWh per year	82 - 860 kWh per year	-		-30%[b]	-5%[b]	-
Hutchins, (2015)	European Average (EU28)	Office and Residential Average	Average of Double Glazing, U = 2.6 W/m²K, G = 0.63 and Double Low E Glazing, U= 1.8 W/m²K, G = 0.63.	Averaged SW & NE	184 Mtoe [c]	79 Mtoe [c]	263 Mtoe [c]	External Shutter & Internal Roller Blind	- 30% [c]	-14% [c]	- 19%[c]
Dubois, (2001)	Stockholm, Sweden	Office	Double Glazing U = 2.6 W/m²K, G = 0.86	South	≈23 kWh/m²yr	≈77 kWh/m²yr	100[d] kWh/m²yr	External Awning 1. Fixed,	≈ - 83%	43%	≈ 14% [d]
								2. Seasonal	≈ - 81%	≈ 6%	- 14% [d]
								3. Dynamic.	≈ - 83%	0	- 20% [d]
				North	≈10 kWh/m²yr	≈100 kWh/m²yr	110[d] kWh/m²yr	1. Fixed,	≈ - 60%	≈10%	≈ 4% [d]
								2. Seasonal	≈ - 60%	≈ 4%	- 2% [d]
								3. Dynamic.	≈ - 60%	0	- 5% [d]

[*] Positive percentages are an energy penalty and negative percentages are an energy saving.
[a] Total End Use Energy (including equipment and lighting), [b] Average heating and cooling demand penalty/saving over multiple simulation scenarios [C] Based on 70% requirement for heating and 30% for cooling end use energy in the EU28 building stock [d] Annual heating and cooling demand only.

The studies reviewed and summarised in Table 5 have all been carried out using various building simulation packages and a variety of different inputs were incorporated within the studies. The inputs varied in weather data sets used, building typologies examined, building orientation and latitude, building construction and the glazing and shading types considered. The energy outputs of the studies also varied, with energy savings being reported in terms of the total end use, primary or delivered energy.

Even though there were relatively few similarities between the studies there were some common outcomes. In all the studies when the ‘with shading’ scenario was compared against the ‘without shading’ scenario the inclusion of shading products provided a greater cooling demand energy saving than a heating demand energy saving. In a few of the studies it was acknowledged that the inclusion of moveable shading resulted in a heating energy penalty but on all occasions where this occurred the energy penalty was offset by the amount of cooling energy saved (PHYSIBEL, 2005; Seguro and Palmer, 2016). The research suggests that the heating energy required for a building is sensitive to the opening and closing strategy chosen for shading products and incorporated in the thermal simulations. All studies took a different approach to simulating blind and shutter movements. The strategies that provided both heating and cooling energy savings varied depending on the external weather conditions or the type of thermal energy in use (Dubois, 1998; Hutchins, 2015; Wouter et al., 2010). Those studies that examined different orientations of the glazed area all agreed that shading was more effective at saving cooling energy on southern orientated facades as opposed to northern orientated facades (Dubois, 1998; Hutchins, 2015; PHYSIBEL, 2005; Wouter et al., 2010). There was also a general consensus that as the U-value of the glazing improved the heating energy savings reduced (Dubois, 1998; Hutchins, 2015; PHYSIBEL, 2005; Wouter et al., 2010).

When relating these studies to the impact shading could have on the potential energy savings in the UK. It is important to realise that most buildings already incorporate internal shading presently and these findings suggest that more care should be taken over the position of blinds to ensure wanted solar gains are not lost from leaving shading products closed, as this can result in more heating energy being used to heat buildings. In the UK it is less common to see moveable external shading installed on buildings and these studies suggest that in buildings where cooling might be needed or already relied on to provide thermal comfort there is a sizeable economic and environmental benefit to be had from the installation of moveable external shading products. This benefit will increase if climate change continues to warm external temperatures and the frequency of hot weather events. In buildings where the requirement for cooling is relatively small (< 200 kWh) external shading could help prevent and/or delay the installation of cooling systems or alternatively reduce the sizing and the energy demand of cooling systems. This will help reduce the energy required to operate cooling systems and minimise the environmental impact of the cooling systems installed in buildings.

2.6.5 Embodied Carbon and Life Cycle Assessments

In 2019 the UK Green Building Council (UKGBC) called on the building industry to act and be accountable by working towards the Net Zero Emissions goals outlined by the World Green Building Council which improve upon the European legislative goals (European Commission, 2010, 2015). A framework for analysis was outlined by the UKGBC and Advancing Net Zero (2019) which considers not only the operational energy in buildings but also the embodied carbon and end-of-life impact of buildings. This requires conducting a full Life Cycle Assessments (LCA) to identify the environmental impact of building materials and products used within buildings. The existing framework identifies shading as a measure in reducing operational energy consumption however, a complete LCA of the varying shading systems available is required to ensure the overall environmental impact of shading product systems (embodied carbon and operational energy) is beneficial to reducing the environmental impact of buildings. To be considered beneficial the operational energy savings need to outweigh the embodied carbon and the associated environmental impacts created throughout the products lifetime i.e., from ‘cradle to cradle’.

The process of Life Cycle Assessments is outlined by BS EN 14040 (BSI, 2006b) and the calculation method of construction works is provided in BS EN 15978 (BSI, 2011). Royal Institute of British Architects (Sturgis, 2017) splits the stages of LCA into modules and provides guidance on how LCA can fit within the bounds of the design and delivery stages of a building. Below is a list of the stages in a products lifetime that LCAs need to consider:

- Raw material extraction and bulk material processing
- Component manufacture and assembly
- Transport and installation
- Operational use
- Treatment at end-of-life

It is also worth noting that whilst transportation is included in a particular step it should also be incorporated wherever relevant. For example, this may be considered within the raw material extraction and material processing step.

The type of LCA carried out can vary depending on the purpose of the analysis. The different types of analysis are referred to as either a 'Comparative LCA', a 'Product LCA' or a 'Screening LCA'. The 'Comparative LCA' compares the environmental impact of a product against other products or product variant. A 'Product LCA' provides a descriptive analysis of how a specific product effects their environment throughout the products lifetime and a 'Screening LCA' is often used in research and provides a rough estimation and assessment of environmental impacts by considering the most relevant materials and resources using average data (ifu Hamburg, 2021).

Product labelling in the form of Environmental Product Declarations (EPD) relies on the LCA methodology. However, currently EPDs only require the initial stages to be included within the declaration this covers the 'Product Stage' extraction of materials up to manufacture and assembly (BSI, 2012). This is referred to as a 'cradle to gate' assessment. However, there are options to include additional modules if preferred by manufacturers. EPD data can be attached to a building model via Building Information Modelling (BIM) to provide a greater understanding of the environmental impact of a building and help support full building LCAs to be carried out (Obrecht et al., 2020). This LCA data can then be paired with accurate building simulation models in the design stage which estimate the operational energy required to maintain a building. This data could then be used to identify a more holistic environmental impact of a product and be used to quickly identify more environmentally beneficial options of designing buildings. Building designs could then be benchmarked against one another based on their environmental impact to produce more environmentally friendly and energy efficient buildings.

There are currently very few drivers in the UK that encourage either LCA or EPDs, therefore data regarding shading products and LCAs is limited (ASPB, 2020). Prior research that identifies the environmental impact of shading products have focused on the 'Carbon Footprint' of shading products and whilst these are useful and provide a guide of the environmental impacts, they only consider one metric measure, carbon, and its associated impacts. LCAs are more comprehensive and include the measure of hundreds of material, gas and liquid inputs and outputs including emissions to land, air and water, the impact on ecosystems, resource supply and human health (Bibalou et al., 2014; Birgisdóttir and Rasmussen, 2016; BSI, 2006). However, carbon footprint studies can still provide a useful indication of the environmental impact of products in terms of carbon. One such study was carried out by the Würzburg Schweinfurt Institute (ES-SO, 2014) who calculated the impact of a standard external motorised venetian blind (1.2m x 2.0m) on a building in Germany.

The system produced 150 Kg of CO_2 and this was offset 57 times throughout its 20-year lifespan as it was able to save 8.5 tonnes of CO_2 by reducing the consumption of energy used within the building.

An LCA study (Babaizadeh et al., 2015) conducted across the US in differing climates on residential buildings evaluated the impact of five simplistic external shading products made solely out of wood, aluminium or PVC. At the end-of-life 75% of the wooden shading product was sent to landfill and 25% was incinerated as waste, whilst 100% of the aluminium and PVC were recycled. The study concluded that wood had the best environmental and economic impact, followed by aluminium and then PVC. Whilst these results are interesting the study took an overly simple approach to the product evaluation as in reality shading products are made up of a variety of materials and associated manufacturing processes. A similar study was carried out in the UK by Ylitalo et al. (2006) who found that if external roller blinds (1.3 x 2.3m) were recycled at the end-of-life the greenhouse gas emissions would be offset by the operational energy saved in a building within 6 months of operation. However, only the aluminium in the product was assessed and therefore the fabric of the blind curtain and other componentry within the system was not considered in the assessment (BSI, 2018). Additionally, maintenance of the system over its estimated 25-year life span was not considered or included within the assessment. To predict the operational energy saved by the blind the study incorporated the use of a building simulation tool to identify the difference in annual energy savings of a building with and without the shading product installed. The external roller blind was provided a 15% reduction in energy consumption equating to a saving of 68 $kgCO_{2e}$ over a year. The total emissions produced by the product itself totalled 38 $kgCO_{2e}$ and thus were offset within 6 months. The operational energy saved over the 25-year life span would not only offset the CO_2 produced as result of manufacturing and installing the product but also save an additional 1,662 $kgCO_{2e}$ over its lifetime. However, if the product were sent to landfill the life cycle cost would have equated to 215 $kgCO_{2e}$ meaning that it would have only offset the environmental impact of the product after 3 years of operational energy savings.

The studies reviewed have addressed very few shading product types and detailed comparative LCAs between different product types have not been carried out. The impact on operational energy of a building through installing shading varies depending on several parameters identified in Section 2.6.4 (p. 37). Further LCAs that compare environmental impacts of different shading products and that use differing control strategies would be useful. Some of the more recent developments in shading technologies (motorised and automated systems) require more complex componentry (i.e., motors and electronics), which will increase the embodied carbon and environmental impact of these systems. However, the uncertainties surrounding the operational energy savings, the product life span and what happens to shading products at end-of-life are barriers to conducting an accurate LCA and will therefore need further consideration when interpreting results.

2.7 Research Gaps, Aims and Objectives

Overheating and Climate Change

Climate change is one of the biggest barriers to the UK reducing its energy consumption, meeting the net zero energy targets, and keeping the people that live and work in buildings comfortable. Future climate predictions suggest that the impacts of climate change will result in UK buildings needing both cooling and heating energy to maintain thermally comfortable conditions for occupants. Current UK building regulations and voluntary sustainability schemes undervalue the importance of incorporating shading products as a way of improving the resilience of the building stock to climate change. Where within Europe they are well recognised and encouraged to be incorporated within building design for their ability to mitigate solar gains and reduce the energy required for active cooling. Historically overheating has not been considered an issue in the UK and thus there is a lack of real-world research that evidences the extent that shading products can help prevent internal temperatures from increasing. Solar shading products could be beneficial in UK domestic homes as in most homes air conditioning is not installed and therefore better specification and use of shading products in these buildings could help prevent or delay the installation of active cooling.

Therefore, this research looks to:

Aim 1: Investigate the extent that shading products (internal and external) mitigate temperature increase in domestic buildings in the UK.

Objectives:

- Monitor the internal and surface temperatures of two similar rooms within two typical domestic homes during a warmer weather period - one room with shading extended (closed) and one with shading retracted (open).
- Evaluate and compare the overheating risk of the rooms (with and without shading) using existing industry methods of how to evaluate overheating risk in buildings.

- Statistically analyse and compare the difference in temperature increase between rooms with shading and without shading.

Occupant comfort, health, well-being, and productivity

The properties of solar shading products can influence the thermal, visual and acoustic internal environment in domestic and non-domestic buildings (CIBSE, 2015; Seguro and Palmer, 2016; Wouter et al., 2010). Shading products differ from many other products used within buildings as they alter multiple internal environment conditions simultaneously. For example, when shading products are closed, they help reduce internal temperatures (by reducing solar gains) but also attenuate incoming daylight. Research into how the internal environment conditions affect occupants suggests that limited access to daylight can negatively impact occupants' perceptions of visual comfort and their health, well-being, and productivity where exposure to more thermally comfortable temperatures can improve their perceptions of thermal comfort, health, well-being, and productivity. This begs the question that when shading products are closed, and the external conditions are warm, how do occupants perceive the internal environment conditions and how do their perceptions subsequently impact their health, well-being and productivity when compared to a situation where there is no shading present. To date no study has evaluated how the position of shading products subsequently affects occupant health, well-being and productivity although some studies have investigated how certain aspects of comfort alter e.g., perceptions of glare and view (Kent et al., 2014, 2017; Konstantzos et al., 2015; Protzman, Brent, 2015).

Aim 2: Evaluate how internal shading products affect occupants and their internal environments.

Objectives:

- Monitor the internal and external environment conditions of two office work environments, where one of the offices has internal shading products extended (closed) and the other retracted (open).
- Record occupant perceptions of the indoor environment, overall comfort level, perceived health and well-being and objective productivity under the two constraints (open and closed blinds).
- Analyse how the position of the internal shading products (open or closed) affected their perceptions of internal environment, overall comfort level, health and well-being, productivity and there actual (objective) productivity.

The literature review, Chapter 1, revealed that there was some research that suggested that internal shading products can attenuate sound transmitting into buildings (i.e., improve the sound insulation of a building) and help absorb reverberant sound within a room. In certain building designs and in certain circumstances this may be beneficial for improving acoustic comfort as improvements in these aspects help reduce the overall sound level within buildings. For example, in buildings where windows cannot be easily replaced and there are noise disturbances outside, or in heavily glazed office spaces where reverberant noise contributes to the overall sound level in a room. Research literature and testing standards have identified that the acoustic properties of shading products can be quantified. However, there is little information available from shading manufacturers about the acoustic properties of the shading products they supply. The lack of testing conducted on shading products conventionally used in UK domestic and non-domestic buildings makes it hard to viably conclude the extent of the impact shading products have on the transmission of sound and the absorption of sound. From the literature reviewed there appears to be little acoustic benefit as when comparisons were made between a room with and without shading, shading reduced the transmission of sound by < 3 dB which would be barely perceptible by an occupant. The extent that shading products reduce reverberant sound was not fully investigated as no comparison was made between a room with and without a blind. Additionally, only a small number of shading systems and installation scenarios were tested. Further testing of shading systems may provide a benefit to the shading industry and reveal an undervalued performance characteristic of shading products. Furthermore, reviewing the appropriateness of testing standards to benchmark shading fabrics against one another may be useful and lead to the creation of a simpler testing method for shading manufacturers to adopt to be able to pass on acoustic information about the products they supply to building designers, specifiers and consumers. Nevertheless, like the thermal and visual properties the acoustic performance benefits will only be possible to achieve when shading products are extended.

Aim 3: Investigate how different fabrics used in internal shading products influence the internal acoustic environment.

Objectives:

- Review existing testing methods and how they evaluate the acoustic properties of materials and building components.

- Where practical, apply these testing methods to a range of typical internal shading fabrics conventionally installed in domestic and non-domestic buildings.
- Compare the properties of the shading fabrics and theoretically assess to what extent shading products/fabrics will affect the internal acoustic environment using existing acoustic design methods.

Environmental Impact of Shading Products

Existing literature suggests that the energy savings provided by moveable shading products positioned vertical to a window are sensitive to when they are extended or retracted. The shading industry has innovated new systems that incentivise their use (e.g., motorisation) or operate autonomously in an effort to make the operational energy savings more obtainable to building owners. These innovations can also help provide greater energy savings and provide occupants with more comfortable internal conditions. However, these new innovations change a passive product (i.e., a product that does not require energy to operate) into an active product (i.e., a product that consumes energy). It is almost certain that in the 'Product Stage' the environmental impact of automatic and motorised systems will be greater than manually operated shading products because of their need for additional resources, componentry, and more complex manufacturing processes. However, it is unclear whether these innovations can be considered environmentally beneficial over the products lifetime i.e., from cradle to cradle, when taking into account the operational energy savings they provide. This therefore calls for a 'cradle to cradle' LCA to be conducted to evaluate the point at which differing shading products that utilise different control strategies become environmentally beneficial, (i.e., how long do the products have to be installed and used for and how much operational energy do they need to save before the can be considered environmentally beneficial). This will differ depending on the operational energy saved, the embodied environmental impact of the product itself (inclusive of maintenance), the amount of time the product is installed and used for, and how waste materials are treated at end-of-life.

Aim 4: Evaluate the environmental impact of differing shading products that use different control strategies (specifically manual, motorised, and automated shading) and identify at what point the environmental benefit obtained from the operational use of the shading systems offsets the environmental impact of the product itself during its lifetime.

Objectives:

- Conduct screening Life Cycle Assessments based on a typical home in the UK with either internal manual roller blinds, internal motorised roller blinds and external automated venetian blinds installed.
- Compare the environmental impact of the product against the environmental benefits provided through heating and cooling operational savings.
- Identify what environmental benefit needs to be obtained and over how many years before each shading system can be considered environmentally beneficial.
- Consider how changes in operational energy use in UK domestic homes may impact the environmental benefit of shading systems in the future.

2.8 Thesis Structure

Chapter 2, Literature Review, summarises research literature related to solar shading products in the UK and investigates various aspects that would encourage the installation and use of solar shading products. The following chapters include three real-world case studies, two laboratory experiments and one desk-top study that provide further evidence of the impact shading products have on buildings, the environment, and people.

Chapter 3 details the steps taken in two of the three real-world case studies which focus on identifying how internal and external shading products affect internal temperature increase in domestic buildings (Aim 1). Industry methods of evaluating overheating risk (CIBSE TM52 and CIBSE TM59) were used in the analysis of the results in addition to other statistical methods that help compare the effectiveness of internal and external shading products in reducing temperature increase.

In Chapter 4, the third real-world case study is described which investigated how the position of internal shading products, either fully extended (closed) or fully retracted (open), affected the occupants and the internal environment conditions in a naturally ventilated, non-domestic building. 19 participants and the two conditions (blinds open or blinds closed) of the two offices were monitored for 15 days. During this period, they were asked about their perceptions of the indoor environment, their health and well-being and were given work-based and cognitive performance tasks to complete within the two conditions. The analysis uses various statistical techniques to identify relationships between the position of blinds and how they impact internal environments and people to fulfil Aim 2.

Through the literature review (Chapter 2) it was identified that shading products can also affect the internal acoustic conditions of a building. This was not possible to investigate in the real-world case studies so separate laboratory experiments were carried out to review the acoustic properties of shading fabrics, which are one of the factors that influence how effective shading products in absorbing reverberant sound and insulating buildings from external noise pollution. Where possible existing theoretical calculation methods were adapted to include shading fabrics to calculate how effective the shading fabrics were and how they would theoretically affect the indoor environment acoustic conditions. This work is presented in Chapter 5 to satisfy Aim 3.

In Chapter 6 a parallel study was conducted which involved performing a screening Life Cycle Assessment of different shading products that used different control strategies. The products assessed were a manual and motorised internal roller blinds and an automated external venetian blind. The type of shading products chosen (i.e., roller and venetian) based on their conventional use in UK domestic buildings). The environmental impact of the products themselves were compared against the theoretical operational energy savings shading products could provide throughout their lifetime to answer Aim 4.

Each chapter contains a summary of the research findings and Chapter 7 provides the conclusions in relation to the research question and aims along with recommendations for future work.

CHAPTER 3. OVERHEATING IN DOMESTIC BUILDINGS

3.1 Overview

Overheating in the indoor environment, specifically in domestic homes, schools, and healthcare settings, has become of great concern in the UK because of the more frequent hot weather events being experienced. This is a result of the continually rising global average temperatures which are associated with climate change. Overheating is caused by heat gains associated with occupancy and solar heat gains from the sun being trapped in the internal environment. The combination of the continued rise in external air temperatures, improvement in insulation standards in conjunction with poorly planned ventilation strategies are exacerbating experiences of overheating during warmer weather conditions (NHBC Foundation, 2012; Zero Carbon Hub, 2015). In the past decade heat gains associated with occupancy (from lighting and equipment) have reduced through improving the energy efficiency of these products. However, the number of appliances we own and use within our homes continues to increase (DECC, 2012; IEA, 2009, 2019). The rise in the number of buildings that overheat (House of Commons, 2018) and the number of associated deaths due to warmer weather events (PHE, 2019) identifies that it is now crucial that passive measures are utilised appropriately and for building occupants to be educated in how to safeguard their homes against overheating e.g., using blinds correctly and opening windows (CCC, 2019b; Lomas and Porritt, 2017).

This research is centred on two real-world monitoring case studies and investigates how shading systems (internal and external) can mitigate overheating risk through reducing the amount of solar gain entering a building. Two domestic homes were evaluated to assess the impact of shading devices on overheating risk.

New and renovated domestic homes are at a greater risk of overheating as in the UK the vast majority (approximately 97%) do not use active cooling (as opposed to commercial buildings) and are built to higher energy efficient requirements making them more air-tight and thermally retentive. Of the differing domestic home types, apartments are acknowledged to be at a greater risk of overheating. Apartments are often built-in urban areas where noise and air pollution can deter occupants from opening windows as a means of accessing natural ventilation. The layout of apartments often means that openable windows are often placed on only one façade of the building preventing occupants from being able to cross-ventilate. Where windows are present, they are often unshaded and windows on elevations above ground level often have restrictors placed on them to prevent them from being fully opened for safety reasons. New apartments are also often designed to have smaller floor areas, lower ceilings, and larger glazing areas than other building types. Similar to new homes, new and recently renovated apartments are also more insulated and designed to be air-tight with communal heating and hot water distribution pipes running through unventilated corridors which increases internal heat gains (Good Homes Alliance, 2014; Zero Carbon Hub, 2015). Therefore, Case Study 1 evaluated the impact of both internal and external shading combined with night-time ventilation on a newly renovated apartment block, located in Camden, London and built to Part L 2010 standards.

Existing houses in the UK in suburban areas are at less of a risk from overheating. However, if the current strategies that domestic homes have are not effective in combatting the challenges climate change presents (e.g., heatwaves and generally warmer external temperatures) there may be a risk that these homes could potentially overheat in the future. In existing UK domestic homes internal blinds (or curtains) are commonly installed by occupants for a variety of reasons. However, these shading products can also be used in warmer periods to prevent incoming solar gains and help reduce thermal discomfort. Therefore, Case Study 2 evaluated the impact of internal shading on a semi-detached house, built in the 1970s and situated in the more surburban Hampton, Richmond upon Thames.

Within a domestic home, bedrooms present the greatest risk to people's health as occupants are most vulnerable when sleeping as they are less able to adapt and protect themselves from overheating i.e., open windows, turn on electric fans, change their clothing levels etc. Therefore, in both case studies bedroom internal operative temperatures (Θ) and external air temperature (T) data were collected. Supplementary data relating to the acoustic conditions and surface temperatures (S) were also collected. The frequency and time-period of the temperature measurements varied due to the equipment used to collect data and the accessibility to the two buildings. Two differing methodologies were developed to measure the impact of internal and external shading devices on reducing overheating. The methodologies differed to overcome the barriers presented when conducting real-world research. These were:

- Differences in occupancy profiles and subsequent internal heating loads:
    - Case Study 1 was unoccupied during data collection and utilities and electrical appliances were not in use.

    - Case Study 2 was occupied by two occupants, although the bedrooms were unoccupied during data collection the rest of the house was in use. This included the use of utilities (hot water) and electrical appliances.
- Controllability of ventilation strategies:
    - In Case Study 1 a behavioural occupancy schedule was incorporated into the study design. The occupancy was based on a working couple and windows were opened when occupants were assumed to be home and left open at night (between 4 pm and 8 am).
    - In Case Study 2 windows were not opened throughout the monitoring period.
- Practicalities in measurements and equipment:
    - Case Study 1 measurements were taken between 8 am and 4 pm with manual sensors on 20 days when the researcher was given permission to visit the site between August and October 2016. 16 days of this data were analysed.
    - Case Study 2 measurements were taken using automatic data loggers which were set up to collect data for 39 consecutive days between August and September 2016[8]. 26 days of this data was analysed.
- Installation of shading systems:
    - Case Study 1 assessed a variety of internal and external shading devices.
    - Case Study 2 assessed a variety of internal shading devices only[9].

Whilst the methodologies differed between the two studies the use of shading devices and the analysis procedure were the same. In both case studies a control room was created where shading products were not installed. The environmental conditions within the control room were then compared with the remaining test rooms where shading was deployed (i.e., extended or closed).

The shading systems and the material properties used within the two case studies are described within the separate case study methodologies. For Case Study 1 (the apartment)

[8] Environmental monitoring equipment is costly and as the apartment building required multiple rooms to be monitored it was not feasible to use automatic loggers to collect data. Additionally, as the apartment block was undergoing renovation the equipment could not be left unattended. The differences in logging equipment used created differences between the two studies in the frequency and the duration of time that temperature data was collected for.
[9] Case study 2 did not allow for external shading due to the irreversible impact the installation would create on the external of the façade which was not acceptable to the house owners.
However, within Case study 1 it was possible to install differing internal shading products.

shading systems that were considered most effective at rejecting solar gain were tested and for Case Study 2 (the house) shading systems that are considered typical of UK homes were tested[10].

In both case studies the analysis assessed the frequency of overheating; the severity of overheating; and whether the absolute maximum operative temperature (Θ_{upp}) was exceeded according to industry guidance, TM52 Overheating Criteria, produced by the Chartered Institution of Building Services Engineers (CIBSE). A statistical approach was also taken to compare the extent that differing shading strategies reduced the increase in internal temperatures to a 95% confidence interval. Furthermore, in Case Study 2 night-time temperature data were reviewed to compare the number of hours that exceeded 26°C in line with CIBSE TM59 Overheating Criteria (CIBSE, 2013, 2017). A full CIBSE TM59 assessment was not possible to carry out in either case study. This is because at the time the study was carried out (2016) the TM59 assessment method had not been published and therefore sufficient data was not collected to carry out this analysis. In Case Study 1 only daytime temperatures were collected (because of the use of manual sensors and the time restrictions on access to the building) and in Case Study 2 only 39 days of night-time temperature data were collected. The CIBSE TM59 requires a full year of night-time hourly temperature data.

Whilst this study assesses the impact of internal and external shading devices on the reduction of internal temperature, the study design has limitations as the outcomes are only relevant to the specific case study buildings assessed, the shading devices used, and the occupancy patterns incorporated within the case studies. However, as they represent typical building designs[11] and representative occupancy patterns were included within the study design the case study buildings are valued as contributing to research knowledge regarding the potential impact of shading devices in mitigating overheating risk and improving occupant thermal comfort.

3.1.1 Measuring Overheating

Lomas and Porritt (2017) reviewed 12 studies which claimed to identify overheating in domestic homes, in a mix of building types (that varied in age and construction), across the

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[10] Guidance on the product types to be tested was provided by the British Blind and Shutter Association who represent over 500 companies who manufacture, install, and sell shading products throughout the UK.

[11] Semi-detached houses represent 26% of the current UK housing stock and low-rise flats represent 14% (GHA, 2019; MHCLG, 2019a). Close to a million buildings were converted into flats in England in 2011.

UK. Lomas and Porritt concluded within the literature review that the term ‘overheating’ is not clearly defined for post-occupancy evaluations as differing methodologies, data collection procedures and measurements are used within research which makes comparisons between studies problematic. CIBSE recommends two of the most widely known methods of evaluating overheating risk within naturally ventilated and mechanically ventilated buildings, TM52 and TM59, which cover differing building typologies. TM52 (CIBSE, 2013), addresses all building typologies (domestic and commercial) through a three criteria assessment procedure. The method was developed to test the design of buildings in the early design stage where building modelling simulation tools are used to predict the performance of the building.

The three criteria system aims to assess the frequency, severity and sets an absolute maximum temperature for overheating. Overheating is deemed to be a problem if two of the following three criteria occur:

1. The operative temperature, Θ, exceeds the maximum acceptable operative temperature, Θ_{max}, by 1°C for more than 3% of hours between May and September (the typical non-heating season).
2. The weighted exceedance, W_{ε}, exceeds the maximum acceptable operative temperature, Θ_{max}, by more than 6 degree-hours in any one day.
3. The maximum acceptable operative temperature, $\Theta_{max,}$ is exceeded by 4°C at any time (which is termed the absolute maximum operative temperature, Θ_{upp}).

For real-world case studies it is suggested that internal operative temperature, Θ, and external air temperature, T, data is collected over a period of at least 10 days which is representative of weather conditions (CIBSE, 2015).

Operative temperature, Θ, considers internal air temperature T_{int} and mean radiant temperature, mrt, into a single value. It is a weighted average of the two and the weights are based on the heat transfer coefficients by convection (which is varied by air velocities) and radiation at the clothed surface of a person. CIBSE recommend that the √(10 v), where v is the air velocity in meters per second, is used as the ratio for heat transfer resulting in the following formulae to calculate operative temperature:

$$\Theta = \frac{T_{int}\sqrt{(10\ \mathrm{v})}+mrt}{1+\sqrt{(10\ \mathrm{v})}} \qquad \text{(Equation 1)}$$

When indoor air velocities are < 1 m/s, natural convection is assumed to be equivalent to 0.1 m/s and the operative temperature formulae can be simplified to:

$$\Theta = \ ^1\!/_2\ T_{int} + \ ^1\!/_2\ mrt \qquad \text{(Equation 2)}$$

In real-world experiments the Θ approximates closely to the temperature at the centre of a black painted globe that is 40 mm in diameter (CIBSE, 2015).

Criterion 1 is limited to the 'occupied' hours for building modellers, but this is not defined in post occupancy evaluations due to the acknowledged difficulties surrounding data collection. Additionally, if there is only data available for a portion of the summer months then 3% of the available hours should be used (CIBSE, 2015).

The Θ_{max} threshold used in CIBSE TM52 is variable because it is based on the theory of 'adaptive thermal comfort' which is the theory that an occupants' acceptability of the internal environment covers a wider range of temperatures because of their connection with the outdoors and their ability to adapt the internal environment to obtain their preferred thermal comfort (e.g., wearing lighter clothing and opening windows). The Θ_{max} in CIBSE TM52 therefore considers the running mean external air temperature, T_{rm}, of the previous days, the building type (e.g., recently renovated/new or existing) and the vulnerability of occupants as vulnerable occupants are less able to adapt their internal environments appropriately (BSI, 2015; CIBSE, 2013; Nicol et al., 2013).

More recently the TM59 (CIBSE, 2017) methodology was developed to specifically address overheating risk in homes. Naturally ventilated homes need to meet two criteria which are relevant to the type of room being assessed (i.e., bedrooms, living rooms and kitchens). Criterion A in TM59 is the same as criterion 1 in TM52 and bedrooms, living rooms and kitchens are assessed against this criterion. Criterion B places further emphasis on bedrooms and highlights the importance of comfort during sleeping hours. It sets a more stringent limit on the number of hours a bedroom can overheat for and uses a set temperature threshold instead of the variable Θ_{max}. In naturally ventilated homes the fixed threshold is 26°C in operative temperature which should not exceed by more than 1°C for more than 1% of annual hours at night (10 pm - 7 am) (i.e., 32 hours) and mechanically ventilated homes should not exceed 26°C for more than 3% of the annual occupied hours. However, there is no guidance on how to apply this criterion if annual temperature data is not readily available making it problematic to apply to real-world monitoring where only a portion of annual temperature data is collected and more suitable for assessing internal temperatures produced through building simulation tools.

In addition, TM59 strongly recommends that an alternative occupancy profile should be used for building modelling predictions of overheating risk. A 24-hour occupancy profile should be assumed for a one-bedroom apartment and at least one person should be assumed to be in each bedroom in the daytime in a two-bedroom apartment and two people in each double bedroom at night. Window opening behaviours are also addressed and should be assumed to be open when the dry bulb internal temperature exceeds 22°C. The benefit of the TM59 method is that it tests the design of the building to mitigate overheating by evaluating lengthy occupied periods and it also addresses the unpredictability of occupancy when the building is in use. Furthermore, it helps account for the fact that a growing number of occupants work from home (which was crucial for many during the COVID 19 Pandemic in 2020) and more vulnerable occupants are more likely to be at home in the daytime (Felstead and Henseke, 2017; Office for National Statistics, 2014).

Both methodologies have been incorporated as a statutory requirement into the Draft London Plan (Greater London Authority, 2020). In the current London Plan (Greater London Authority, 2016) both methodologies are recommended alongside the Good Homes Alliance (GHA) Overheating in New Homes Tool and Guidance Document (GHA, 2019) which also refers to CIBSE TM59.

3.2 Case Study 1 Description

3.2.1 Building Overview, Design and Layout

The apartment building located in North London was purpose built in the 1930s for the manufacture of aircraft parts. In the 1980s it was converted into offices (Warner Lofts, 2015) and more recently, in 2014, planning approval was submitted to the local authority to convert the commercial building into twenty residential loft apartments and two penthouse suites located on the third floor. The renovation was completed in 2016 in accordance with UK Building Regulations (2010). The study was conducted within the year of completion.

The south-west façade of the building is situated on a busy main road in the heart of Camden with a 24-hour use bus stop directly in front of the property. Prior to the renovation and as part of the planning application, an external noise survey was carried out in 2014 by a third-party contractor who measured the A-weighted L_{Aeq} and L_{Amax} external noise levels on the roof of the property in accordance with BS 7445-1:2003 (BSI, 2003a) and

BS 4142: 1997 (BSI, 1997a). Measurements were documented as being measured at 15-minute intervals over 4 consecutive days, including a weekend, on the roof of the property. The external noise levels at night (11pm – 7am) were recorded at 98 dB L_{Amax} and a 65 dB L_{Aeq}. During the day (7am – 7pm) a 67 dB L_{Aeq} was recorded. The calculated noise level at the bedroom windows at the front of the property was predicted to be 68 dB $L_{Aeq,1hr}$. 38 dB above the recommended 30 dB for occupant comfort (CIBSE, 2015). Therefore, the acoustic consultant specified a glazing that would achieve the desired sound reduction for the bedrooms (Soundplanning, 2014). The glazing specified had a 200mm cavity gap between two panes of glass 10 and 6mm thick. The researcher observed that the recommendation from the acoustic consultant had not been carried forward and a double low emissivity argon filled glazing (4-16-4) with a black/grey spacer which fit into steel mullion framework had been installed.

The façade design offered little external shading although a communal garden area was developed at the front of the building which consists of a 1.8m wooden fence surround containing newly planted young evergreen oak trees that provide privacy and shading to the ground floor apartments and potentially the first floor of the building in years to come (Figure 6). The construction was a mix of brick, concrete and timber flooring throughout the building and the buildings thermal mass was considered light weight according to the SAP methodology (106.31 kJ/m^{2}K).

Figure 6. South-West facing building close to Camden High Street Underground Station (Photograph was taken with a wide-angled lens).

3.2.2 Monitored Rooms

The twenty apartments were spread over four floors between the basement level to the second floor. The central apartments on the 1st and 2nd floor (Apartment 13 and 18) were selected for monitoring as the internal layouts were identical (see Figure 7). They also had the same orientation, provision of external shading provided by neighbouring buildings and the overhangs were almost identical. Therefore, the external façade of the apartments were exposed to similar weather conditions.

Figure 7. (Above) First floor building layout with Apartment 13 highlighted (Below) Second floor building layout with Apartment 18 highlighted.

Figure 8 shows the single aspect layout of the apartment with highly glazed façade orientated south-west. Each apartment contained a living room, kitchen, bathroom and two rooms designed as bedrooms on the south-west side of the building.

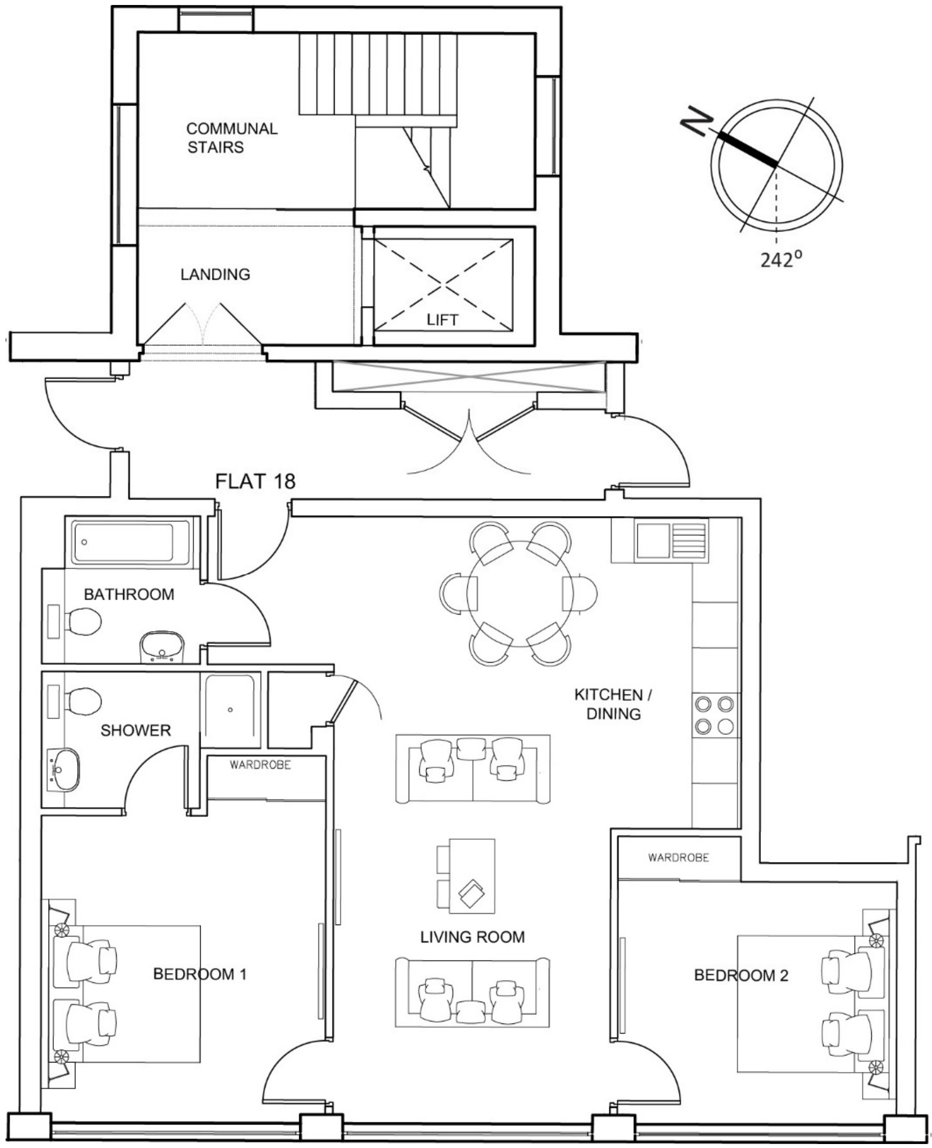

Figure 8. Apartment 13 and 18 Layout of Case Study 1

The two bedrooms in both apartments were chosen to be monitored as there were no differences between the rooms other than the room depth. Bedroom 1 was 4.5 m deep where Bedroom 2 extended to just 3.5 m. The ceiling height was 2.6 m and the room width was 3.5 m. The walls and floors were finished and painted to the same standard - matt white paint on the walls and oak wood flooring and there was no furniture present in either apartment.

3.2.3 Façade Design

Each of the bedrooms had a glazed area that had been refitted during refurbishment with double low emissivity argon filled glazing (4-16-4) with a black/grey spacer which fit into a steel mullion framework. The glazed areas were of equal size covering 3200 mm x 1850 mm, with a window to external wall ratio of 65% and openable area of less than 13% via two top hung windows (850 mm x 450 mm) located in the centre column (Figure 9).

Figure 9. Window view from Apartment 13, Bedroom 1 (Case Study 1)

3.2.4 Solar Shading Products Tested

During the study three internal and two external solar shading products were tested. The venetian blind was tested when tilted at a 45° and fully closed, where the rest of the shading products were only tested when fully closed.

Internal Blinds

- Aluminium venetian blind (fully closed)
- Internal screen fabric roller blind
- Internal reflective screen fabric roller blind

External Blinds

- Aluminium Venetian blind (fully closed)
- Aluminium Venetian blind (45°)
- Screen fabric roller blind

The solar properties of each blind type were provided by the manufacturers of the shading products and are presented in Table 6. The g_{tot} values were calculated using BS EN ISO 52022-1 (BSI, 2017) methodology and the g_{tot} identifies the total solar energy transmittance entering into a room or building. The exact g_{tot} of the case study shading and glazing scenarios could not be calculated due to a lack of glazing data (e.g., the G-value was not supplied) therefore the g_{tot} in Table 6 have been calculated with the assumption that the shading is combined with the properties of standard reference glazing C which represents a double glazed unit with a low emissivity glazing system (4-16-4mm), space filled with argon. The U-value of 1.2 W/m^2 and G-value of 0.59 are given in BS EN 14501:2005 (BSI, 2021b) for reference glass C. The lack of specific glazing data has not compromised the study as the same type and size of glazing was used in the control (without shading) and the shaded rooms.

As previously mentioned, the shading products in this study were chosen based on their perceived effectiveness to reduce solar gain entering the building defined by the shading properties in Table 6 which are simplified into a calculated g_{tot} which considers both the properties and positioning of the shading and the type of glazing the shading is combined with. Internal venetian shading products are commonly found in homes in the UK and screen fabrics are more commonly used in commercial offices as they provide a high level of visual transmission (i.e., amount of daylight).

Table 6. Solar Shading Properties used in Study 1 according to BS EN 14501 (BSI, 2021b)

Blind Fabric	Material Composition	Solar Transmission (τ_e)	Solar Reflectance (ρ_e)	Solar Absorption (α_e)	g_{tot} (Reference Glass C*)	
					Internal	External
Aluminium Venetian	Aluminium (80mm Slats)	0.00	0.50	0.50	0.40	0.04
Aluminium Venetian at 45° Angle	Aluminium (80mm Slats)	0.08	0.38	0.55	0.45	0.10
Screen Fabric	42% Fibreglass / 58% PVC	0.10	0.20	0.70	0.50	0.13
Reflective Screen Fabric	36% Fibreglass / 64% PVC	0.05	0.75	0.20	0.32	N/A

* Reference Glazing C has a U-value of 1.2 W/m^2 and G-value of 0.59 BS EN 14501 (BSI, 2021b).

3.2.5 Occupancy and Equipment

During the investigation the window opening behaviour of an occupant who goes to work during the day was simulated. The apartment would be unoccupied between 8 am and 4 pm, with windows closed for security reasons during the day. Between 4 pm and 8 am the windows were open, as though the apartment was occupied, which enables occupants to take advantage of cooler external temperatures at night to ventilate the building. Electric lighting and equipment were not in use throughout the study and doors to each of the bedrooms remained closed throughout except for when the researcher entered each room to take measurements during the monitoring period.

When evaluating the apartments, the researcher observed that external noise pollution may cause an issue for occupants sleeping. To assess the extent of this acoustic sensors were used to monitor internal noise levels when the windows were open at night.

3.2.6 Data Collection Procedure

3.2.6.1 Temperature Measurements

Data was collected over twenty days between August and October 2016. Before each day of data collection, the windows and joining room doors between the bedrooms and living areas were left open overnight to allow for maximum night-time cooling. Prior to the day of data collection, a different shading device was installed in each room, except for the control room where no blind was installed.

Data collection procedure:

- 8 am – Windows and doors closed; measurements start.
- Globe and air temperature measurements were taken every 10 minutes.
- Surface temperatures were taken every 30 minutes.
- 4 pm – Windows and doors opened; measurements stopped.

The measurements were manually collected which required a researcher to enter each room and record the readings on the sensors. Each time this was done it was carried out in the same way; the door was opened and closed as the individual entered and exited the room being monitored and the instrumentation was left in the same position throughout the testing period. Keeping both the windows and doors closed (except for a brief period) allowed the researcher to assume air velocities within the room were below 0.01 m/s. Therefore, we can assume the raw globe temperature data collected were representative of the operative temperature, Θ (CIBSE, 2015).

Out of the twenty days of data collected, fourteen of the twenty days met the data collection procedure (outlined above). Six days of data in total were discounted for several reasons. On some of the test days the windows had been closed the night previous (after the researcher had left the site) meaning that the rooms had not been ventilated according to the data collection procedure. Therefore, the data collected the following day were discounted. Data was also discounted when the building maintenance team tested the heating system, and the preceding days data was also discounted to ensure the thermal mass of the building had time to cool. Lastly, on two days when internal shading had been installed in the test rooms the control room globe temperature sensor malfunctioned[12]. This meant comparisons of internal globe temperatures could not be made however the surface temperature data collected were still possible to compare.

Operative temperature data when internal shading products were in position were collected across 14 days and when external shading was in position across 11 days. The data collected resulted in 21 scenarios where internal shading data and control room data were collected and 16 scenarios where external shading and control room data were collected.

3.2.6.2 Acoustic Measurements

The second set of data collected aimed to evaluate noise exposure within the rooms if occupants were to open windows at night to reduce internal temperatures through night purge ventilation. After the thermal data was collected acoustic equipment was setup within Apartment 13 on the 2nd floor. Bedroom 1 was setup with the windows open and measurements were taken over four consecutive days between Friday and Monday at L_{Aeq} at 5-minute intervals.

3.2.6.3 Equipment

Internal Globe Temperature (Operative Temperature) – A black globe thermometer (40mm Ø) was used with a mercury thermometer as the temperature probe. The sensor was set up on a tripod and positioned 1.8m from the glazed façade and set at 1.2m from floor level within all four rooms being monitored (Figure 10).

Room A: Control Room (No Blind Installed) Room B: 80mm Aluminium Venetian Blind

Figure 10. Equipment Setup of Case Study 2

Surface Temperature Sensor – A handheld surface temperature probe was used with a Type K thermocouple. The same probe was used to collect both glazing and mullion surface

[12] The mercury temperature probe in the control room that measured the Θ gained an air pocket and therefore the data collected was unreliable.

temperature measurements. The mullion measurements were taken internally from the centre point of the window and the glazing measurements were taken from the centre of the glass panel second from the bottom in the central column (see Figure 9, p. 65).

External Air Temperature - A handheld air temperature sensor was placed on the ground floor outside the apartment building. The sensor was setup in a shaded location and was moved throughout the day to keep it in the shade. This prevented the sensor being affected by direct solar radiation.

Acoustic Sensor - The Nor 140 Sound Analyser replaced the position of the globe temperature sensor in Bedroom 1.

A diagram of the sensor setup is provided in Figure 11.

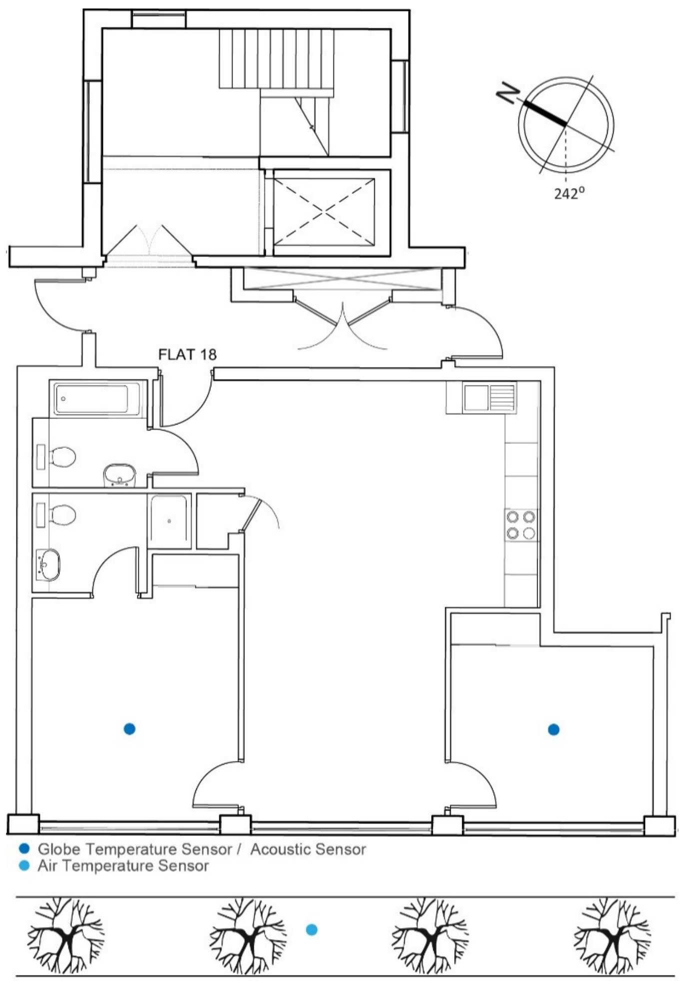

Figure 11. Sensor Layout of Case Study 1

3.3 Case Study 2 Description

3.3.1 Building Overview, Design and Layout

The 1970s semi-detached domestic property was situated in Hampton, Richmond upon Thames and was monitored during summer 2016. The property was arranged over two floors with an adjoining single storey garage. On the ground floor there was a main entrance hall, w.c., kitchen and dining room facing north and a large reception room facing south that lead onto the garden. On the first floor there were four purposely designed bedrooms, en suite shower and one family bathroom. One of the bedrooms on the south side of the building had been re-purposed and furnished as a study. The layout of the properties first floor is shown in Figure 12.

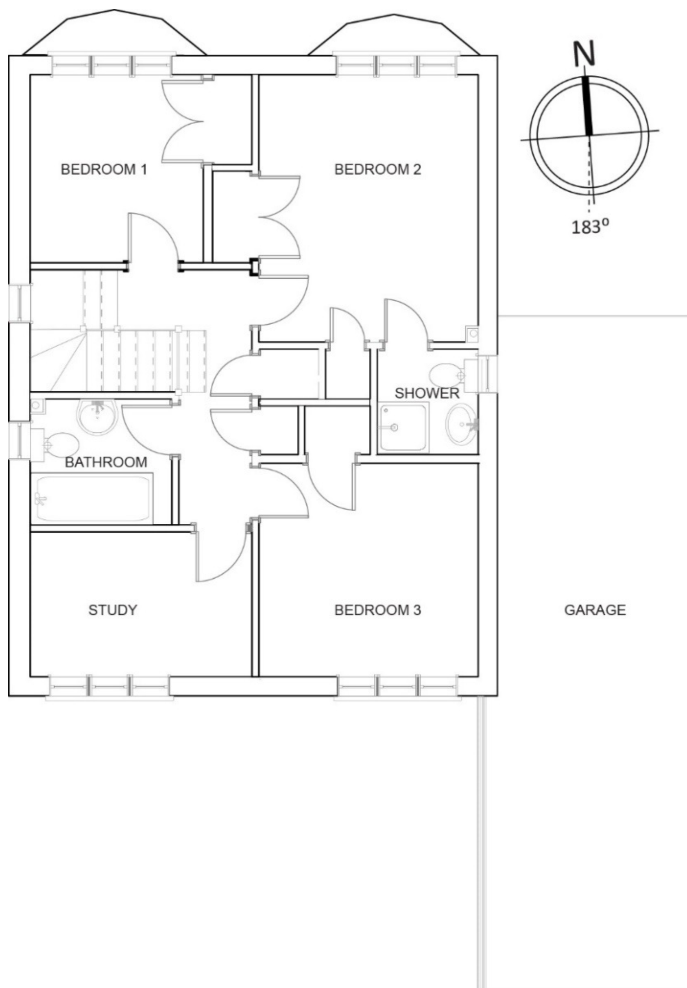

Figure 12. First Floor Layout of Case Study 1

3.3.2 Monitored Rooms

The study and bedroom 3 (from here on referred to as Bedroom) were located on the south side of the building. Both rooms had equal sized glazed areas that overlooked the rear garden. The single storey garage and vegetation in the rear garden did not shade the study or bedroom windows. However, some external shading was provided by the overhang of the roof as can be observed in Figure 13. The two rooms were equal in width and height, although they differed in room depth. The bedroom was 3.2 m (W) x 3.1 m (D), the study was 3.2 m (W) x 2.1 m (D) and the ceiling height was 2.5 m in both rooms.

The décor in both rooms were similar in style: lightly coloured walls with a light beige coloured carpet. However, the furnishings within the rooms differed. The bedroom had a double bed, single cupboard and two storage trunks and the study was furnished with a computer, wooden topped desk, and dark fabric chair with three ceiling height bookshelves across the rear wall and one book shelf along the front wall. Whilst there were differences in room depth and furnishings, the Study and the Bedroom were selected to be monitored as they had the most similar characteristics.

Figure 13. 3D Model of Case Study 2

3.3.3 Façade Design

The glazed area in the bedroom and study was 1770 mm (W) x 1170 mm (H). The occupants of the property were unable to provide an exact glazing specification but were aware that the glazing was double clear with a uPVC surround, and the windows in both rooms had the same specification and were fitted at the same time. Within each room the window to external wall ratio was 26%.

3.3.4 Solar Shading Products Tested

Four internal solar shading products were tested, and these products were chosen based on their common use in domestic homes. Guidance was provided by the British Blind and Shutter Association[13] as to which products were most frequently purchased by homeowners for use in bedrooms. The products chosen varied in type and thermal and visual properties. The products tested included one aluminium venetian blind, one wooden venetian blind, one 100% polyester dimout blind and one honeycomb dimout blind. The dimout shading products are representative of blinds frequently used in bedrooms for their room darkening properties. Venetian blinds offer attenuation of daylight entering a room and thus help optimise natural daylight. Honeycomb blinds (also known as cellular blinds) are more effective at reducing heat losses in winter and subsequently help reduce energy consumption and thermal discomfort in winter.

3.3.5 Occupancy and Equipment

The property was occupied by a working couple, and the building was regularly unoccupied between 7 am and 6 pm[14]. During the monitoring period the computer within the study and internal lighting in both rooms were not used and therefore did not contribute to heat gains within the monitored rooms (study and bedroom). The rooms were unoccupied for the entirety of the monitoring period and the windows and doors to each of the rooms remained closed throughout the study.

3.3.6 Data Collection Procedure

3.3.6.1 Temperature Measurements

External and internal temperature data were collected by a datalogger at 10-minute intervals and averaged over a 30-minute period over 39 consecutive days between August and September 2016. To ensure the data quality, data was discounted on the days that differing shading systems were installed, and the proceeding days data was also discounted. Additionally, data was discounted if the rooms were noted by the occupant to be used e.g., windows or doors opened / office or spare bedroom used by occupants. This was required because keeping both the windows and doors closed allowed the researcher to assume air velocities within the room were below 0.01 m/s and therefore we are able to

[13] The British Blind and Shutter Association represent over 400 manufactures, installers, and retailers of shading products.
[14] These times are an approximation from the occupants as occupancy was not monitored within the study. The occupants were requested to inform the researcher if the rooms were entered during the monitoring period.

assume the globe temperature data collected were representative of the operative temperature, Θ (CIBSE, 2015).

Data met the data quality requirements for 26 of the 39 days of data collected. During the days that data were collected an internal shading system was extended (closed) in the test room and in the control room the shading products were always retracted (opened).

3.3.6.2 Equipment

Datalogger – Two dataloggers were used to automatically collect data. Data was collected at 10-minute intervals and was averaged and output every 30-minutes. The external and internal sensors for the study were connected to one data logger and the internal sensors for the bedroom were connected to a separate datalogger. Both dataloggers and the thermistors used were calibrated prior to data collection by an independent third party.

Internal Globe Temperature (Operative Temperature) – A black globe thermometer (40mm Ø) was used with a thermistor as the temperature probe. The sensor was set up at a height of 1.2 m and positioned 1.55 m from the glazed façade in both rooms being monitored. The accuracy for the thermistor was ±0.2°C between 0 - 60°C[15].

External Air Temperature – A thermistor probe with a radiation screen was used to collect external air temperatures with an accuracy of ±0.2°C between 0 - 60°C[15]. The thermistor was positioned on the roof of the property.

A diagram of the sensor setup is provided in Figure 14.

[15] The temperature sensors and the datalogger were calibrated externally.

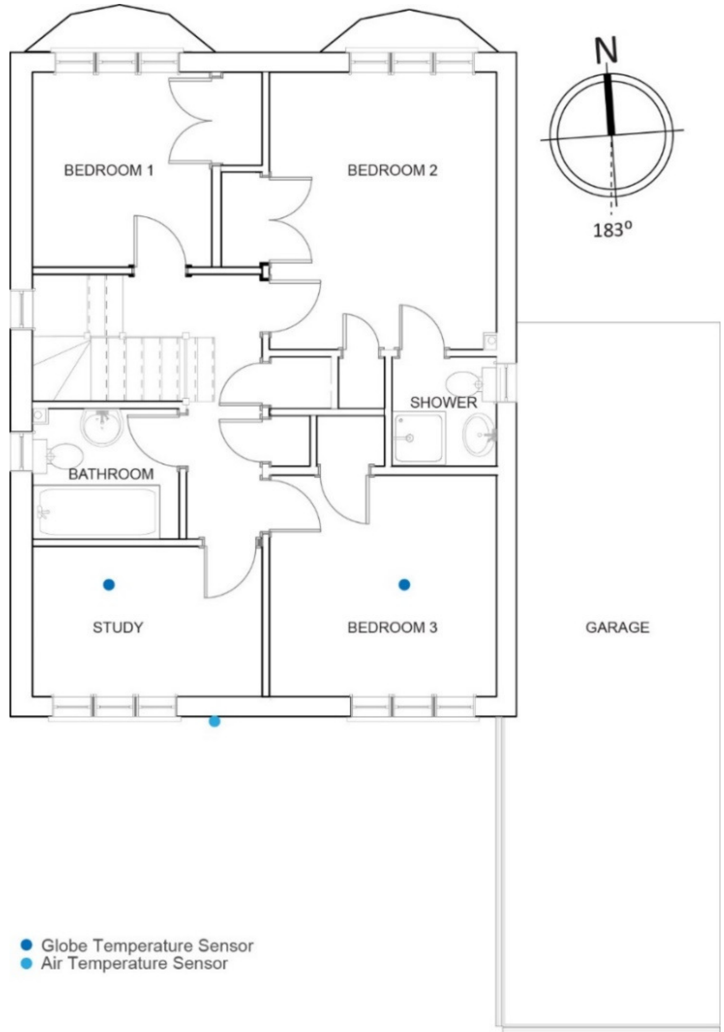

Figure 14. Sensor Layout for Case Study 2

3.4 Method of Analysis

3.4.1 External Weather Conditions

Peak external air temperatures in both case studies were reviewed to establish the variation in external weather conditions during the data collection period. The maximum external air temperatures (T_{max}) were grouped into 15 - 20°C, 20 - 25°C and 25°C +. An equal distribution in the number of days that peak within these temperature thresholds would ensure that the testing was representational of typical low/mid/high summer and autumn weather conditions.

Daily observations and online weather data were made regarding external wind velocities to ensure they could be considered normal for the time of year. CIBSE Guide A:

Environmental Design Guide (CIBSE, 2015) suggests that wind speeds between 2 - 4 m/s are considered normal for summertime when external temperatures vary between 4 and 36°C.

3.4.2 CIBSE TM52: Frequency and Severity of Overheating

As previously described the CIBSE TM52 methodology requires two of the following criteria to be fulfilled to pass the overheating risk assessment. To carry out the assessment for Criteria 1 - 3 the operative temperature data collected at 10 and 30-minute intervals in was converted into hourly average Θ_{1hr} data. Additional external air temperature data was acquired for Case Study 1 to be able to calculate the T_{rm}. This was acquired from the Met Office Weather Station (located 2.8km away at St. James Park, London) who provided Daily Mean Temperature Data for the days monitored.

__Criterion 1: Number of Overheating Hours__

Criterion 1 looks to assess the frequency at which overheating occurs and limits the number of hours over the maximum acceptable operative temperature (Θ_{max}) to 3% during summer (May to September). In both case studies the full summer period was not monitored and in this case it is recommended that at least 10 days of data is collected and assessed to be considered representational of summer conditions (BSI, 2015; CIBSE, 2013).

To analyse the results the monitored hourly averaged operative temperatures (Θ_{1hr}) for the control room (without shading) and the rooms with shading are graphed against the exponentially weighted running mean external air temperature (T_{rm}) with the maximum acceptable operative temperature threshold, Θ_{max}. The Θ_{max} defines the adaptive temperature threshold in °C (Equation 3) and is derived from the exponentially weighted running mean external air temperature, T_{rm} (°C) and the suggested acceptable range that occupants can tolerate (k, in °C). In simpler terms the Θ_{max} is influenced by the external air temperatures of the previous few days; the ways occupants can modify their body temperatures and occupant expectations of building temperatures.

$$\Theta_{max} = 0.33\, T_{rm} + 18.8 + k \qquad \text{(Equation 3)}$$

The T_{rm} considers the mean outdoor air temperature of the previous seven days and applies a heavier weighting to the days closest to the day in question (Equation 4).

$$T_{rm} = \frac{(T_{od-1} + 0.8\, T_{od-2} + 0.6\, T_{od-3} + 0.5\, T_{od-4} + 0.4\, T_{od-5} + 0.3\, T_{od-6} + 0.2\, T_{od-7})}{3.8} \qquad \text{(Equation 4)}$$

T_{od-1} = Daily Mean External Temperature of the day before monitoring

T_{od-2} = Daily Mean External Temperature two days before monitoring

The suggested acceptable range (k, measured in °C) considers adaptive measures that occupants take to protect themselves from overheating (such as wearing lighter clothing), the building category and the vulnerability of the occupants. These categories are defined by BS EN 15251 (BSI, 2015) and are described in Table 7.

Table 7. Suggested Acceptable Temperature Range for differing categories of buildings and occupants (applicable to free-running buildings).

Category	Definition	Suggested Acceptable Range (k, in °C)
I	High level of expectation only used for spaces occupied by very sensitive and fragile persons	± 2
II	Normal expectation (for new buildings and renovations)	± 3
III	A moderate expectation (used for existing buildings)	± 4
IV	Values outside the criteria for the above categories (only acceptable for a limited periods)	> 4

In this thesis criteria 1 has been assessed against Category I for both studies and Category II for Case Study 1 and Category III for Case Study 2. These vary because of the condition of the building, i.e., Case Study 1 has recently been renovated where Case Study 2 has not, and to assess the impact on vulnerable persons.

Criterion 2: Daily Weighted Exceedance

Criterion 2 refers to the weighted exceedance (W_ε) which is based on the sum of the number of hours when overheating occurs (h_n) and an applied weighting factor (WF), which is presented in Equation 5.

$$W_\varepsilon = \sum(h_n \times WF) \qquad \text{(Equation 5)}$$
$$= (h_{n^0} \times 0) + (h_{n^1} \times 1) + (h_{n^2} \times 2) + (h_{n^3} \times 3)\ldots$$

The WF is the difference between the actual monitored temperature (Θ_{1hr}) and the Θ_{max} (i.e., WF = $\Theta_{1hr} - \Theta_{max}$) rounded to 1°C. The WF is zero if the difference between the Θ_{1hr} and the Θ_{max} is zero or a negative value. However, if the difference between the monitored temperature (Θ_{1hr}) and the Θ_{max} is 1 then the WF = 1 and if it is 2 then the WF = 2 and so on. The h_n represents the frequency (number of hours) of the WF. The W_ε should be less than or equal to 6 in any one day to pass the criterion. Further examples of how to calculate the Daily Weighted Exceedance are provided in CIBSE: TM52 (CIBSE, 2013).

Criterion 3: Absolute Maximum Daily Temperature.

Criterion 3 requires the Θ_{upp} to be calculated according to Equation 6. To pass the criteria the Θ_{upp} should not be exceeded on any one day.

$$\Theta_{upp} = \Theta_{max} + 4\,℃ \qquad \text{(Equation 6)}$$

3.4.3 CIBSE TM59: Night-time Overheating

Within TM59 (CIBSE, 2017) it specifies that Criterion 2 and 3 of the TM52 methodology may fail to be met in domestic homes, but Criterion 1 for living rooms, kitchens and bedrooms should be passed and bedrooms should additionally pass the following criteria:

B. *For bedrooms only*: Operative temperatures in bedrooms should not exceed 26°C between 10 pm to 7 am for more than 1% of annual hours to ensure comfort during the sleeping hours (i.e., temperatures should not exceed more than 26°C between 10 pm to 7 am for > 32 hours).

This is assessed in a similar way to criterion 1 within TM52. However, the threshold temperature no longer considers the previous days weather conditions or the suggested acceptable range but a fixed value of 26°C. Additionally, only night-time temperatures are assessed as the aim is to protect occupants from overly warm environments at night.

In this study this criterion could not be applied to the data collected in either case study as annual night-time temperatures were not collected. However, in Case Study 2 twenty-six days of night-time hourly data were collected between August and September in 2016. Therefore, the number of hours in each of the rooms (e.g., with internal shading and without shading) that exceeded the 26°C temperature threshold were examined and compared.

3.4.4 Mitigation of Daily Operative Temperature Increase

In both case studies the temperatures recorded in the test and control rooms differed first thing in the morning. This was likely caused by the variation in thermal retention between the rooms (i.e., different blinds were installed in each room affecting the U-Value of the window system) and in case study 1 there were potential differences in natural ventilation rates between the rooms with and without shading. Additionally, in Case Study 1, having differing shading devices extended (closed) in the test rooms at night may have prevented cooler air entering the rooms at night when the rooms were being naturally ventilated. Therefore, the operative temperature increase, termed $\Delta\Theta$, was calculated which is the difference between the maximum temperature (Θ_{max}) and minimum temperature (Θ_{min}) collected within a test day (i.e., $\Theta_{max} - \Theta_{min} = \Delta\Theta$). In both studies the $\Delta\Theta$ between 8 am and 4 pm[16] was calculated and then analysed using a means comparison Paired t-Test. A Paired t-Test is a statistical method which compares two sets of data that are dependent samples (i.e., they are related) and identifies whether the two sets of data significantly differ. In both case studies the paired t-Test analysis was used to examine whether the $\Delta\Theta$ differed between a room with without shading. Within Case Study 1, data was collected for more than one internal or external shading type on the same day and therefore the averaged $\Delta\Theta$ was used within the paired t-Test analysis.

The paired t-Test also allows for the difference in °C to be identified to a 95% confidence level which is useful in understanding the extent that a shading device (internal or external) impacts the $\Delta\Theta$. It is important to note that the Paired t-Test results are only relevant to each set of dependent samples and therefore the results cannot be compared between case studies as the two case studies are independent of each other as the studies were undertaken in different buildings with different design constraints placed on them (e.g., different building typologies, layout, location, orientation, weather conditions and mitigation strategies considered).

The same method of analysis was applied to the surface temperature data collected within Case Study 1. This examined the temperature increase of the glazing (ΔS_{glaz}) and mullions ($\Delta S_{mullion}$) when differing shading strategies were used.

3.4.5 Acoustic Evaluation

Within Case Study 1 additional data regarding the internal acoustic conditions were collected. The acoustic data logged at a frequency of 5-minute intervals over 4 days with the windows opened. The four days logged included a weekend and two workdays. The data was first averaged to provide a L_{Aeq} for the four days that took into consideration work rush hour traffic and periods of time at night where external noise would be reduced. In addition, the L_{Aeq} and the L_{Amax} was calculated for night-time hours (11 pm – 7 am) and daytime hours (7 am – 11 pm). These results were compared with the measurements reported during the planning application (Soundplanning, 2014) and the recommended internal noise comfort thresholds as defined in CIBSE Environmental Design Guide A (CIBSE, 2015).

[16] 8 am and 4 pm was chosen as this was the earliest and latest measurement taken within Case Study 1 and for ease of comparison the same method was used in Case Study 2.

3.5 Case Study 1 Results

3.5.1 External Weather Conditions

A summary of the external temperature data collected in relation to the type of data collected is presented in Table 8. Each monitored day was given an ID which was kept consistent between the surface and operative temperature datasets. T_{min} and T_{max} represents the minimum and maximum external air temperature recorded on each day, respectively. The ticks and crosses in Table 8 identify what type of shading (internal or external) was monitored on each day. One shading system (internal or external) was applied to each of the three-bedrooms and the remaining bedroom had no shading installed and was used as the control room.

On two of the sixteen days internal operative temperatures were not recorded in the control room (Day 4 and 5) due to a sensor issue which could not be rectified until Day 6. On Days 4 and 5 the operative temperature data in the shaded rooms (crosses highlighted in grey in Table 8) was collected but for the purposes of this research it was discounted as the control room data was needed to make comparisons between the shaded and non-shaded rooms. However, comparisons between surface temperature measurements between shaded and non-shaded rooms were still possible to collect and thus they were used in the preceding analysis.

External shading measurements were not collected as frequently as internal shading systems as they required more time to install and uninstall. An external shading device was installed on Day 2, but monitoring did not begin until Day 3 to allow the building to cool overnight from the solar gains absorbed into the room during the day. On Day 6 the first type of external blind tested was uninstalled, and a differing type of external shading was installed on Day 7 and so monitoring resumed on Day 8. External wind velocities were considered normal during all sixteen days of data collection.

Table 8. External Minimum (T_{min}) and Maximum (T_{max}) Air Temperatures

		External Air Temperatures (°C)		Data Collection Type					
Day ID	Date	T_{min}	T_{max}	Operative Temperature			Glazing and Mullion Surface Temperatures		
				No Shading	Internal Shading	External Shading	No Shading	Internal Shading	External Shading
1	24.08.16	22.4	34.2	✓	✓	×	✓	✓	×
2	25.08.16	22.5	31.1	✓	✓	✓	✓	✓	✓
3	26.08.16	20.8	27.9	✓	✓	✓	✓	✓	✓
4	30.08.16	17.3	28.3	×	×	×	✓	✓	✓
5	01.09.16	16.7	28.4	×	×	×	✓	✓	✓
6	08.09.16	19.7	25.5	✓	✓	×	✓	✓	×
7	28.09.16	14.3	23.2	✓	✓	×	✓	✓	×
8	29.09.16	16.9	20.4	✓	✓	✓	✓	✓	✓
9	30.09.16	13.2	20.1	✓	✓	✓	✓	✓	✓
10	03.10.16	10.5	21.4	✓	✓	✓	✓	✓	✓
11	05.10.16	13.0	20.5	✓	✓	✓	✓	✓	✓
12	06.10.16	13.5	18.7	✓	✓	✓	✓	✓	✓
13	11.10.16	9.9	18.2	✓	✓	✓	✓	✓	✓
14	12.10.16	12.3	16.4	✓	✓	✓	✓	✓	✓
15	13.10.16	11.1	16.0	✓	✓	✓	✓	✓	✓
16	14.10.16	4.5	15.3	✓	✓	✓	✓	✓	✓
	Total Number of Instances			14	14	11	16	16	13

✓ = data collected, × = data not collected, × = data collected but discounted from analysis due to malfunctioning globe sensor in control room.

The following is a summary of the data provided in Table 8:

Operative Temperatures

- Over the 14 days where data was used to compare operative temperatures between internally shaded rooms and unshaded rooms, maximum external temperatures exceeded 25°C on four days and on the remaining ten days the external maximum temperatures were evenly distributed between 20 - 25°C and 15 - 20°C.
- Over the 11 days where data was used to compare operative temperatures between externally shaded rooms and unshaded rooms, maximum external temperatures exceeded 25°C on two days, remained between 20 - 25°C for four days and the remaining five days peaked between 15 - 20°C.

Surface Temperatures

- Over the 16 days where data was used to compare surface temperatures between internally shaded rooms and unshaded rooms, maximum external temperatures exceeded 25°C on six days and on the remaining ten days the external maximum temperatures were evenly distributed between 20 - 25°C and 15 - 20°C.

- Over the 13 days where data was used to compare surface temperatures between externally shaded rooms and unshaded rooms, maximum external temperatures exceeded 25°C on four days, remained between 20 - 25°C for four days and the remaining five days peaked between 15 - 20°C.

In general, the external temperatures were cooler on the days when external shading data was collected in comparison to the days where internal shading data was collected. The weather conditions were considered typical for the summer / autumn period in London.

3.5.2 CIBSE TM52: Frequency and Severity of Overheating with Internal & External Shading

Criterion 1: Number of Overheating Hours

Figures 15 and 18 graph the measured hourly average internal operative temperature (Θ_{1hr}) without shading and with internal and external shading. These are plotted against the exponentially weighted running mean external air temperature (T_{rm})[17] as per BS EN 15251 and CIBSE TM52 (BSI, 2015). The calculated Θ_{max} (dashed line) and Θ_{upp} (red line) are also given in Figure 15 and 18. The Θ_{max} represents the maximum acceptable operative temperature as per BS EN 15251 (BSI, 2015)[18] and the Θ_{upp} represents the absolute maximum daily temperature according to Criterion 2. In this case study we have reviewed the criteria against Category I (K=2) and Category II (K=3) thresholds[19]. Each scatter plot on the graph that exceeds the Θ_{max} limit by 1°C represents 1 hour of overheating (e.g., 2 – 3 pm) as per Criterion 1. Figure 16 - 17 and Figure 19 - 20 provide a daily temperature profile for each day monitored. Figure 16 and 17 compare the rooms with and without internal shading and Figure 19 and 20 compare the rooms with and without external shading. The daily temperature profiles identify the increase in the hourly average internal operative temperature (Θ_{1hr}), the external air temperature (T_{1hr}) throughout the day and the calculated T_{rm}, Θ_{max}, and Θ_{upp}.

[17] T_{rm} considers the mean outdoor air temperature of the previous seven days and applies a heavier weighting to the days closest to the day in question, see Equation 4 (p. 75).

[18] CIBSE TM52 definition of Θ_{max} is derived from the exponentially weighted running mean outdoor air temperature (T_{rm}) and the suggested acceptable temperature range that occupants can tolerate (K), see Equation 3 & 4 (p. 75).

[19] Category I refers to occupancy by fragile and vulnerable persons and Category II refers to the normal expectation for new builds or renovations, see Table 7 (p. 76).

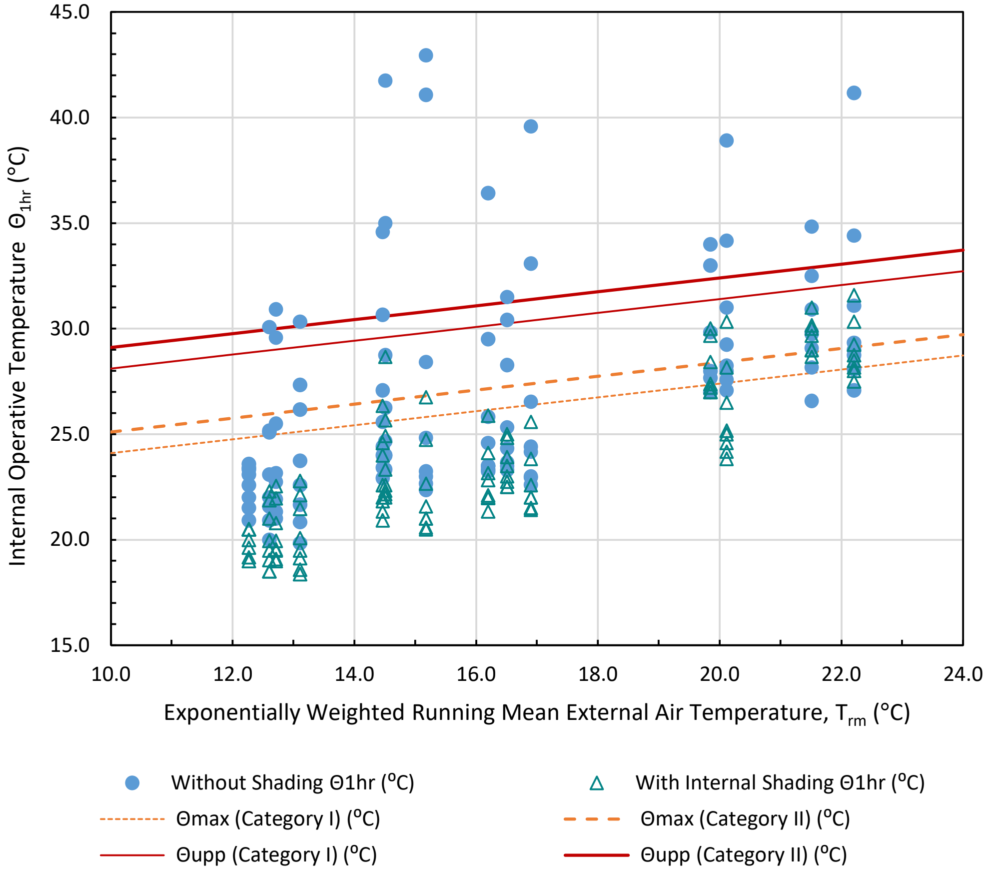

Figure 15. Scatter plot of hourly average indoor operative temperature (Θ_{1hr}) plotted against the exponentially weighted running mean external air temperature (T_{rm}) with plots relating to rooms with no shading (●) and rooms with internal shading (Δ) (112 monitored readings).

No Shading vs Internal Shading (Category I)

- When the rooms without shading were evaluated 35.7% of the hours were equal to or exceeded the Θ_{max} by 1°C, which is equivalent to 40 hours of the total 112 hours monitored.
- When the rooms were internally shaded 13.4% of the hours were equal to or exceeded the Θ_{max} by 1°C, which is equivalent to 15 hours of the total 112 hours monitored.

No Shading vs Internal Shading (Category II)

- When the rooms without shading were evaluated 28.6% of the hours were equal to or exceeded the Θ_{max} by 1°C, which is equivalent to 32 hours of the total 112 hours monitored.

- When the rooms were internally shaded 8.0% of the hours were equal to or exceeded the Θ_{max} by 1°C, which is equivalent to 9 hours of the total 112 hours monitored.

Criterion 1 was failed when rooms without shading and rooms with internal shading were evaluated.

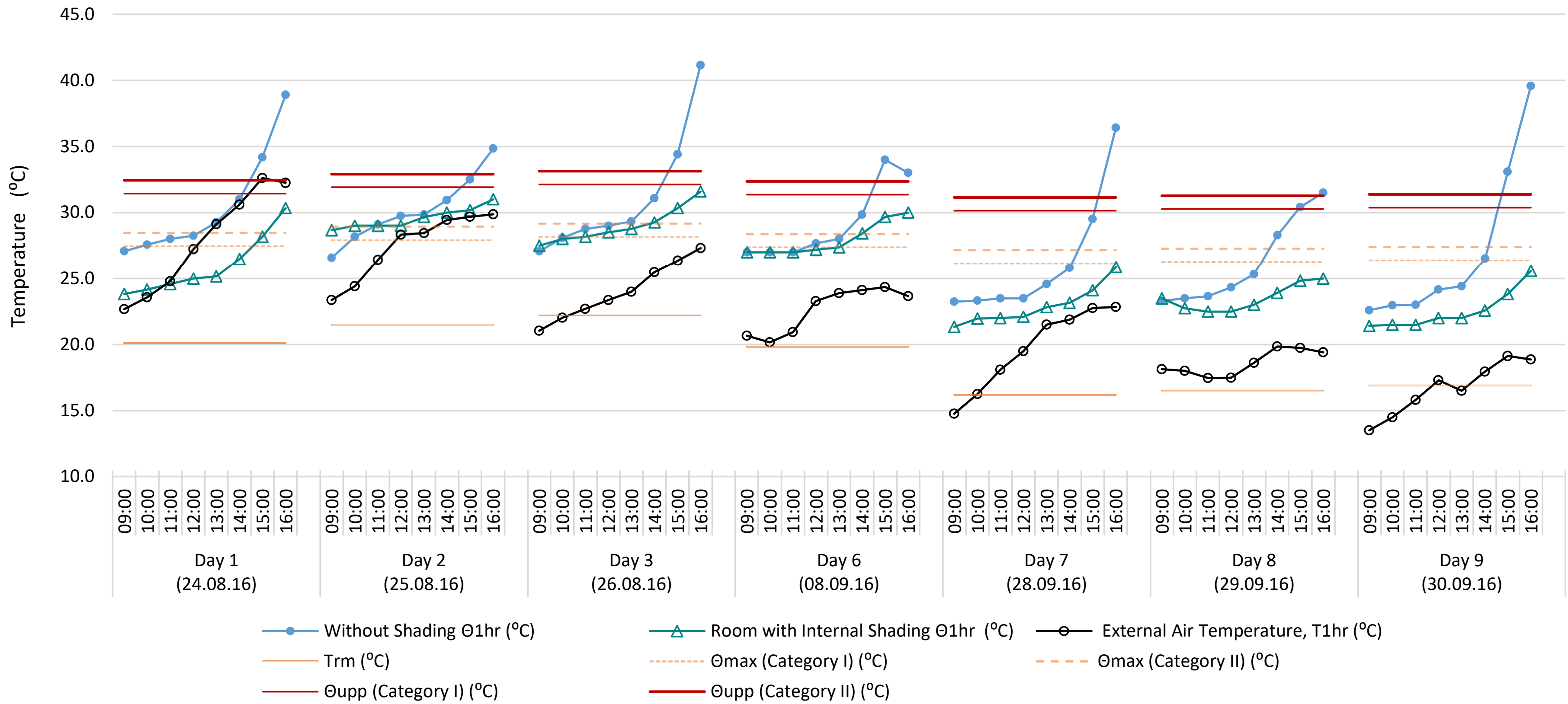

Figure 16. Daily temperature profiles comparing the measured hourly average external air temperature (○), internal operative temperature for rooms with (△) and without internal shading (●), the exponentially weighted running mean air temperature (T_{rm}), the internal maximum acceptable operative temperature (Θ_{max}) and the absolute maximum operative temperature (Θ_{upp}) for the days monitored in August and September 2016 (Graph 1 of 2).

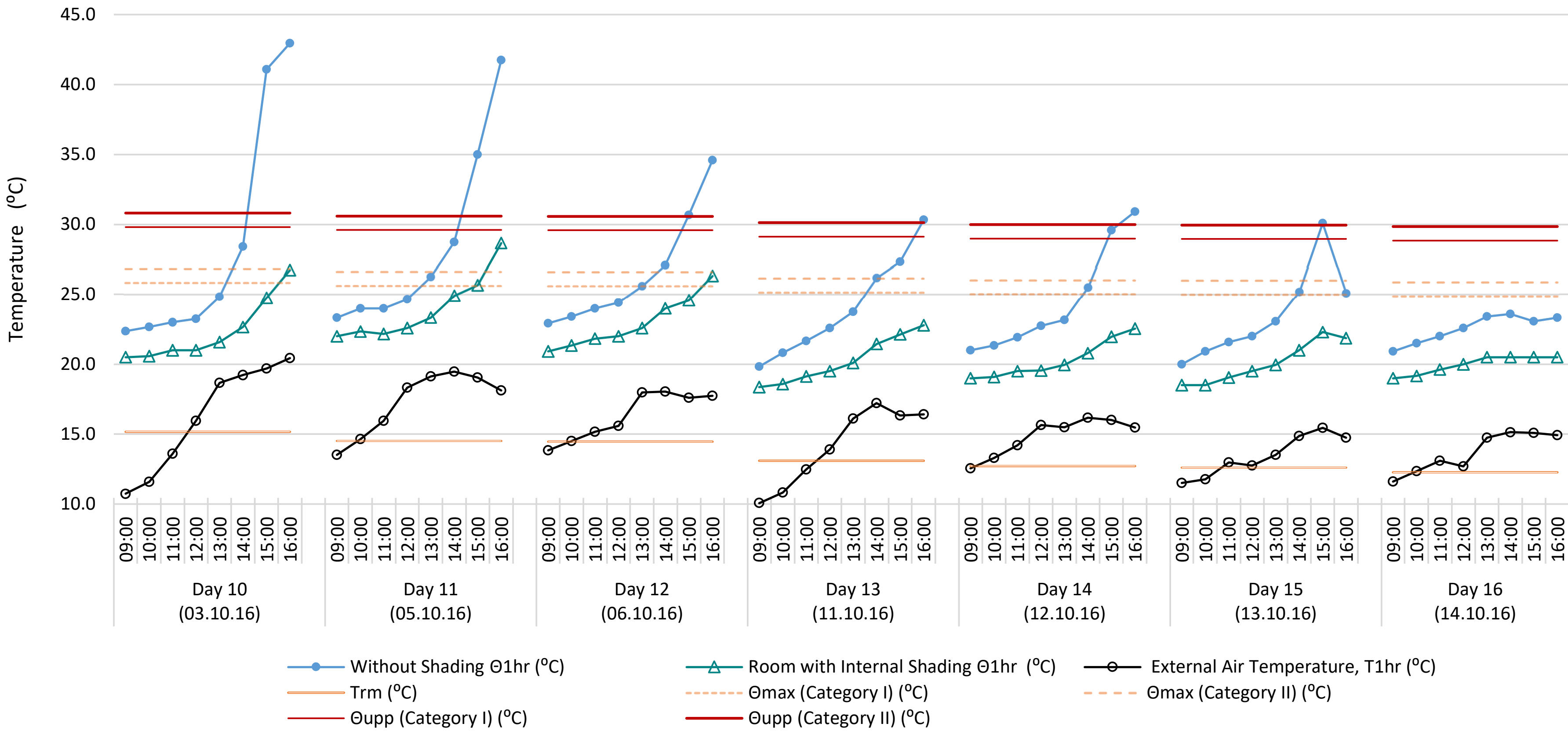

Figure 17. Daily temperature profiles comparing the measured hourly average external air temperature (○), internal operative temperature for rooms with (Δ) and without internal shading (●), the exponentially weighted running mean air temperature (T_{rm}), the internal maximum acceptable operative temperature (Θ_{max}) and the absolute maximum operative temperature (Θ_{upp}) for the days monitored in October 2016 (Graph 2 of 2).

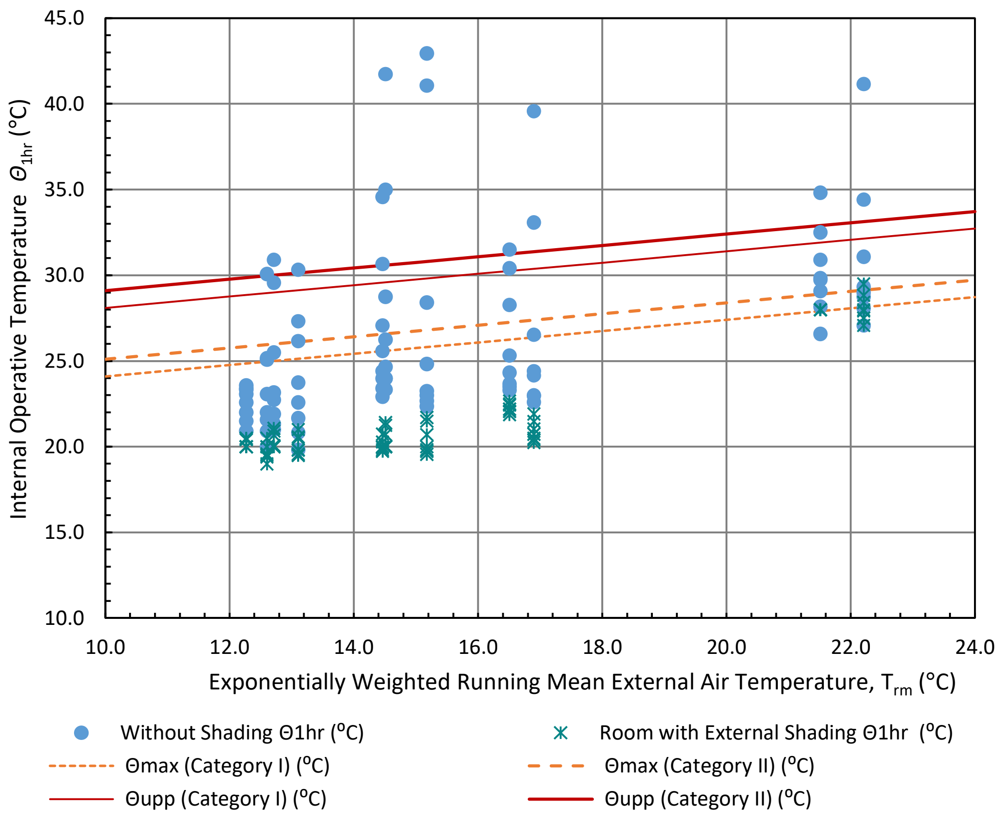

Figure 18. Scatter plot of hourly average indoor operative temperature (Θ_{1hr}) plotted against the exponentially weighted running mean external air temperature (T_{rm}) with plots relating to rooms with no shading (●) and rooms with external shading (*) (80 monitored readings).

No Shading vs External Shading (Category I)

- When the rooms without shading were evaluated 31.3% of the hours were equal to or exceeded the Θ_{max} by 1°C, which is equivalent to 25 hours of the total 80 hours monitored.
- When the rooms were externally shaded 1.3% of the hours were equal to or exceeded the Θ_{max} by 1°C, which is equivalent to 1 hour of the total 80 hours monitored.

No Shading vs External Shading (Category II)

- When the rooms without shading were evaluated 26.3% of the hours were equal to or exceeded the Θ_{max} by 1°C, which is equivalent to 21 hours of the total 80 hours monitored.
- When the rooms were externally shaded the Θ_{max} was not exceeded.

Criterion 1 was failed for rooms with no shading but was passed when rooms had external shading. These results are further summarised in Table 9.

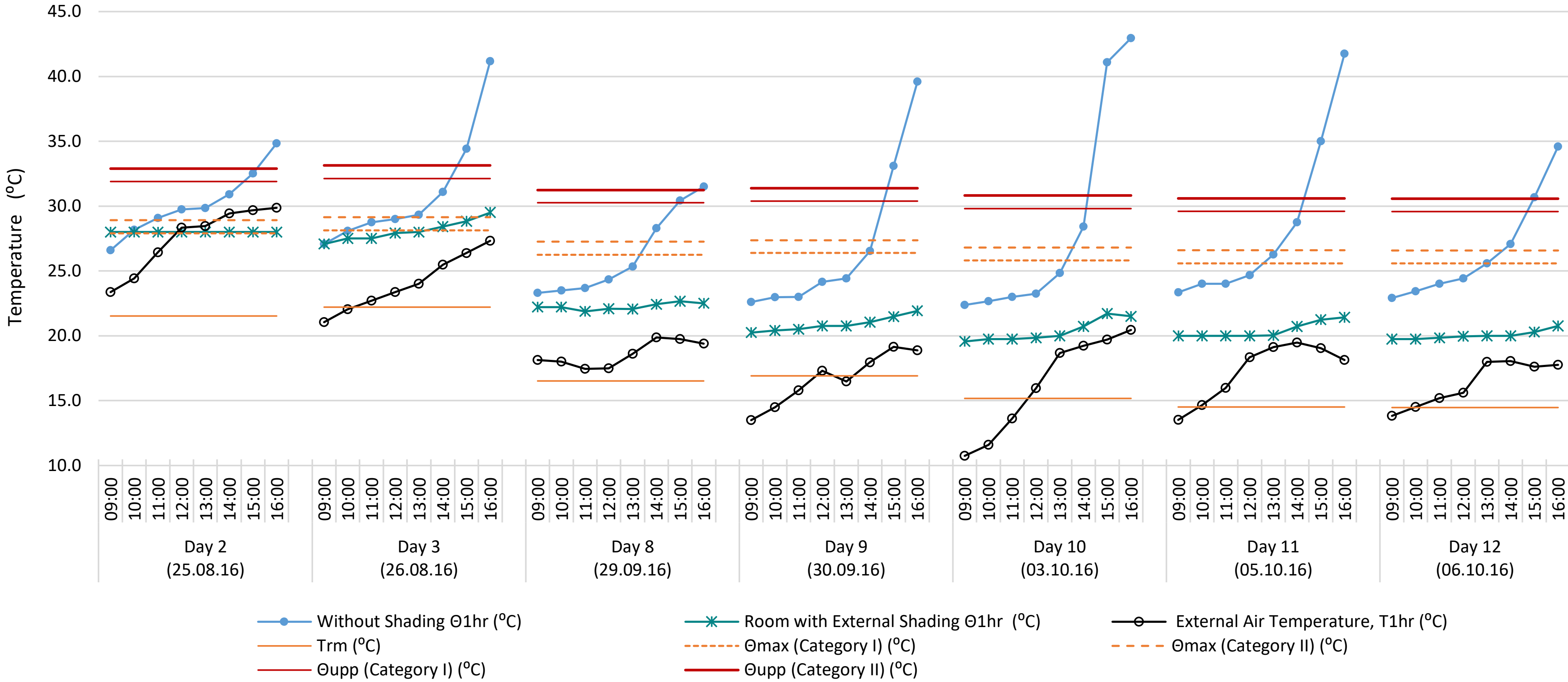

Figure 19. Daily temperature profiles comparing the measured hourly average external air temperature (○), internal operative temperature for rooms with (*) and without external shading (●), the exponentially weighted running mean air temperature (T_{rm}), the internal maximum acceptable operative temperature (Θ_{max}) and the absolute maximum operative temperature (Θ_{upp}) for the days monitored in August, September and October 2016 (Graph 1 of 2).

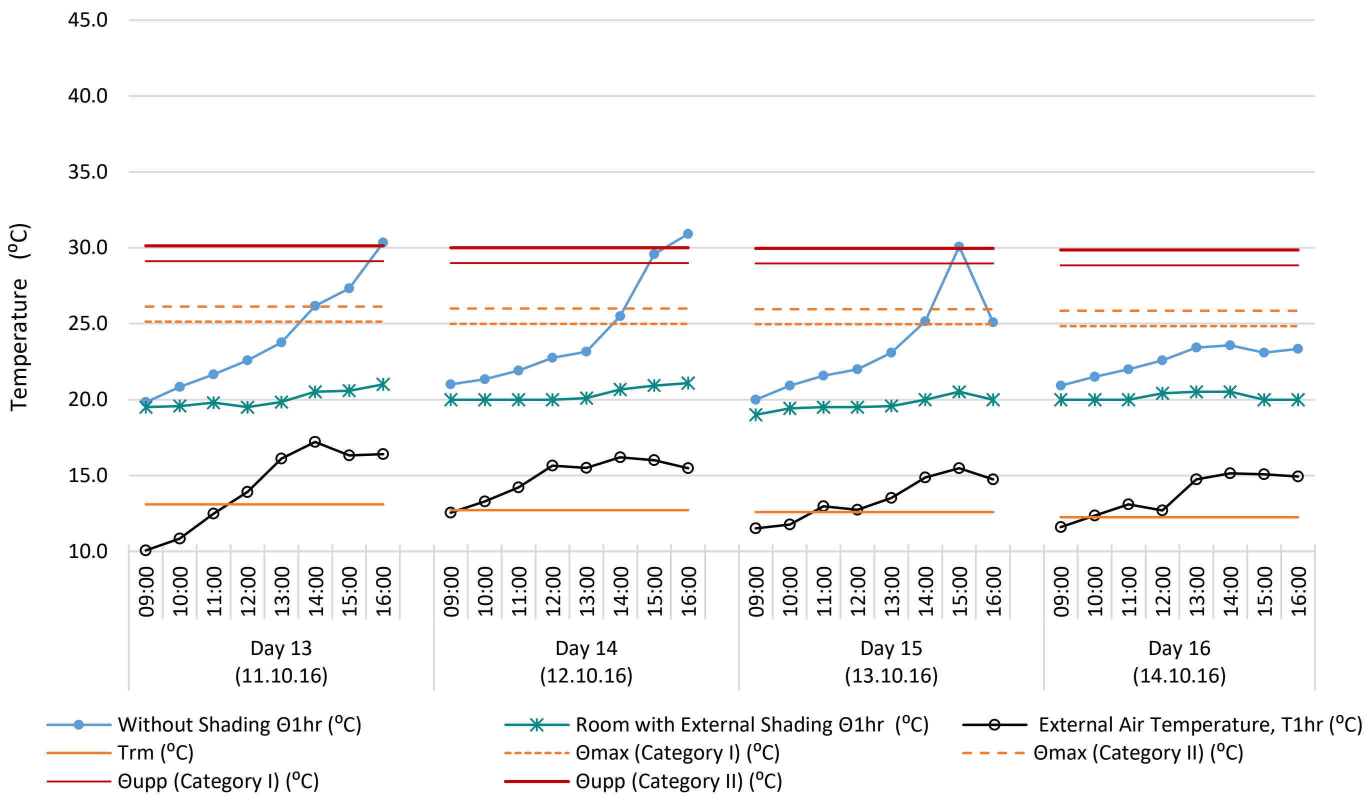

Figure 20. Daily temperature profiles comparing the measured hourly average external air temperature (○), internal operative temperature for rooms with (*) and without external shading (●), the exponentially weighted running mean air temperature (T_{rm}), the internal maximum acceptable operative temperature (Θ_{max}) and the absolute maximum operative temperature (Θ_{upp}) for the days monitored in October 2016 (Graph 2 of 2)

Table 9. Summary of the number of overheating hours and the percentage of monitored hours according to the suggested comfort ranges.

Monitored Scenario	Monitored Hours	No. of Hours that exceed Θ_{max} by 1°C	% of Hours that exceed Θ_{max} by 1°C	No. of Hours that exceed Θ_{max} by 1°C	% of Hours that exceed Θ_{max} by 1°C
		Category I		Category II	
No Shading	112	40	35.7%	32	28.6%
Internal Shading	112	15	13.4%	9	8%
No Shading	80	25	31.3%	21	26.3%
External Shading	80	1	1.3%	0	0%

The percentage reduction between the non-shaded room and the internally shaded room in the number of hours that exceeded the Θ_{max} by 1°C identifies that the presence of internal shading reduced the number of hours by 62.5% for Category I occupancy and approximately 72% for Category II occupancy, and the presence of external shading reduced the number of hours by approximately 96% for Category I occupancy and 100% for Category II occupancy.

In August, the sun was at a higher altitude than in October. In Figure 16 on Day 3 in August the non-shaded room had a peak Θ_{1hr} of 41°C when the T_{rm} was 22°C. In Figure 17 on Day 10 in October the highest Θ_{1hr} in the non-shaded room was recorded at 43°C when the T_{rm} was measured at 15°C. Due to the orientation of the building and the unobstructed window area the author can hypothesise that the peak Θ_{1hr} (43°C) in October in the non-shaded room occurred when the T_{rm} was substantially lower because the lower altitude sun enabled solar radiation to enter the building for a longer duration of time in October than in August. This subsequently caused overheating events in October as well as August.

Criterion 2: Daily Weighted Exceedance

The individual days monitored and scenarios where internal and external shading was used in rooms were reviewed. The weighted exceedance (W_ε) was calculated using Equation 5 (p. 76) for each day monitored with either no shading, internal or external shading in use.

No Shading

- The recommended W_ε limit was exceeded on 7 of the 14 days monitored.

Internal Shading

- During the 21 scenarios, across 14 days where rooms with internal shading systems were evaluated. The recommended W_ε was not exceeded in any of the scenarios.

External Shading

- During the 16 scenarios, across 14 days where rooms with external shading systems were evaluated. The recommended W_e was not exceeded in any of the scenarios.

Criterion 2 was not met when rooms had no shading device, but the criterion was passed when rooms had either internal or external shading.

Criterion 3: Absolute Maximum Daily Temperature

Figure 15 and Figure 18 also present the absolute maximum temperature that should be experienced within a day termed Θ_{upp}[20] for both Category I and Category II type occupation.

No Shading vs Internal Shading (Category I & II)

Figure 15 compares rooms with and without internal shading.

- When rooms without shading were evaluated the Θ_{upp} was exceeded on 13 out of the 14 days monitored.
- When rooms with internal shading were evaluated the Θ_{upp} was not exceeded.

No Shading vs External Shading (Category I & II)

Figure 18 compares the rooms with and without external shading.

- When rooms without shading were evaluated the Θ_{upp} was exceeded on 9 of the 11 days monitored.
- Similarly, when rooms with external shading were evaluated the Θ_{upp} was not exceeded.

Criterion 3 was failed when rooms had no shading device, but the criterion was passed when rooms had either internal or external shading closed.

3.5.3 Mitigation of Daily Operative Temperature Increase

The increase in internal operative temperature, ΔΘ, glazing and mullion surface temperature, ΔS, and external air temperature, ΔT, were calculated in °C for each testing scenario (e.g., with internal, external and no shading). The Δ are presented in Table 11 - Table 15 and were used in the inferential statistics carried out.

[20] $\Theta_{upp} = \Theta_{max} + 4°C$, see Equation 6 (p. 77).

Table 10 presents the findings from the paired t-Test of operative temperatures. These indicate that in all cases there was a significant difference between the operative temperature increase (ΔΘ) in the non-shaded room (control room) and the operative temperature increase (ΔΘ) in the internal and externally shaded rooms. Figure 21 provides a visual representation of the differences between the 95% confidence intervals for the internal and externally shaded rooms and the means of each paired sample.

Table 10. Means Comparison Paired t-Test of the averaged difference in Operative Temperature Increase (ΔΘ) between rooms with and without internal and external shading.

Pair	No. of Paired Samples	Mean (°C)	SD (°C)	SEM (°C)	95% Confidence Interval of Difference: Lower (°C)	95% Confidence Interval of Difference: Upper (°C)	t - statistic (°C)	Degrees of Freedom	*p*
No Blind vs Internal Shading	14	10.71	3.75	1.00	8.54	12.88	10.68	13	<0.001*
No Blind vs External Shading	11	14.32	4.86	1.46	11.06	17.58	9.80	10	<0.001*

*Level of significance, $p < 0.05$.

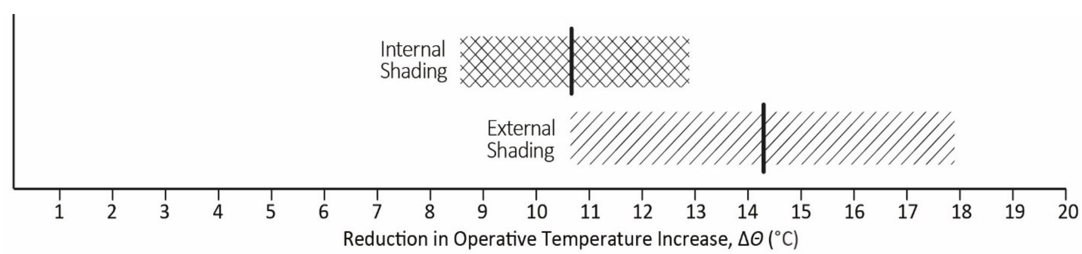

Figure 21. Mean and 95% confidence interval of the reduction in Operative Temperature Increase, ΔΘ, between rooms with and without internal and external shading.

The analysis identifies with 95% confidence that:

- Internal shading will reduce the operative temperature increase by between 8.54°C - 12.88°C. The room with internal shading would therefore be 8.54°C - 12.88°C cooler than a room without shading.
- External shading would reduce the operative temperature increase in the room by between 11.06°C - 17.58°C. The room with external shading would therefore be 11.06°C - 17.58°C cooler than a room without shading.

Table 11. Minimum ($_{min}$), Maximum ($_{max}$) and the Temperature Increase (Δ) of the External Air Temperatures (T) and Internal Operative Temperatures (Θ) over 16 days monitored between 8 am – 4 pm. The solar shading specified was fixed at a closed lowered position or a closed 45° angle for the entirety of the day.

		External Air Temperature (°C)			Operative Temperature (°C)																							
					No Blind			Internal Blinds												External Blinds								
								Aluminium Venetian			Aluminium Venetian at 45°			Fabric 1			Fabric 2			Aluminium Venetian			Aluminium Venetian at 45°			Fabric 1		
Day ID	**Date**	T_{min}	T_{max}	ΔT	$Θ_{min}$	$Θ_{max}$	ΔΘ	$Θ_{min}$	$Θ_{max}$	ΔΘ	$Θ_{min}$	$Θ_{max}$	ΔΘ	$Θ_{min}$	$Θ_{max}$	ΔΘ	$Θ_{min}$	$Θ_{max}$	ΔΘ	$Θ_{min}$	$Θ_{max}$	ΔΘ	$Θ_{min}$	$Θ_{max}$	ΔΘ	$Θ_{min}$	$Θ_{max}$	ΔΘ
1	24.08.16	22.4	34.2	11.8	26.5*	45.0*	18.5	23.5	31.0*	7.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	25.08.16	22.5	31.1	8.6	25.0	40.0*	15.0	-	-	-	-	-	-	28.0*	31.0*	3.0	-	-	-	28.0*	28.0*	0.0	-	-	-	-	-	-
3	26.08.16	20.8	27.9	7.1	27.0*	47.5*	20.5	-	-	-	-	-	-	27.0*	32.0*	5.0	-	-	-	-	-	-	27.0*	29.5*	2.5	-	-	-
6	08.09.16	19.7	25.5	5.8	27.0*	36.0*	9.0	26.0	30.0*	4.0	-	-	-	-	-	-	27.0*	31.0*	4.0	-	-	-	-	-	-	-	-	-
7	28.09.16	14.3	23.2	8.9	23.0	39.0*	16.0	21.0	26.0	5.0	-	-	-	21.5	27.0	5.5	21.0	26.5*	5.5	-	-	-	-	-	-	-	-	-
8	29.09.16	16.9	20.4	3.5	23.0	33.5*	10.5	-	-	-	-	-	-	-	-	-	22.5	25.0	2.5	21.0	22.5	1.5	-	-	-	22.0	24.0	2.0
9	30.09.16	13.2	20.1	6.9	22.5	42.0*	19.5	-	-	-	-	-	-	-	-	-	21.0	26.5*	5.5	20.0	21.5	1.5	-	-	-	20.5	23.0	2.5
10	03.10.16	10.5	21.4	10.9	22.0	45.0*	23.0	-	-	-	-	-	-	-	-	-	20.5	28.0*	7.5	20.0	22.5	2.5	-	-	-	19.0	26.0*	7.0
11	05.10.16	13.0	20.5	7.5	23.0	44.0*	21.0	-	-	-	22.5	30.5*	8.5	-	-	-	-	-	-	20.0	21.0	1.0	-	-	-	20.0	22.0	2.0
12	06.10.16	13.5	18.7	5.2	22.5	39.0*	16.5	-	-	-	20.5	27.0*	6.5	-	-	-	-	-	-	20.0	20.5	0.5	-	-	-	19.5	21.0	1.5
13	11.10.16	9.9	18.2	8.3	19.5	38.0*	18.5	18.5	24.0	5.5	-	-	-	18.0	23.0	5.0	-	-	-	-	-	-	19.5	21.5	2.0	-	-	-
14	12.10.16	12.3	16.4	4.1	21.0	37.0*	16.0	19.5	24.0	4.5	-	-	-	18.5	22.5	4.0	-	-	-	-	-	-	20.0	21.5	1.5	-	-	-
15	13.10.16	11.1	16.0	4.9	20.0	32.5*	12.5	-	-	-	19.0	24.0	5.0	18.0	21.5	3.5	-	-	-	-	-	-	19.0	21.0	2.0	-	-	-
16	14.10.16	4.5	15.3	10.8	20.5	24.5	4.0	-	-	-	19.0	21.0	2.0	19.0	20.0	1.0	-	-	-	-	-	-	20.0	20.5	0.5	-	-	-

* Operative Temperature (Θ) > 26°C

3.5.4 Surface Temperature Reduction with differing Shading Strategies

Table 12. Minimum Temperatures ($_{min}$), Maximum Temperatures ($_{max}$) and Temperature Increase (Δ) of External Air Temperatures (T) and Internal Glazing Surface Temperatures (S_{glaz}) over 16 days monitored between 8 am - 4 pm. The solar shading specified was fixed at a closed lowered position or a closed 45° angle for the entirety of the day.

		External Air Temperature (°C)			Glazing Surface Temperatures (S_{glaz} in°C)																							
					No Blind			Internal Shading												External Shading								
								Aluminium Venetian			Aluminium Venetian at 45°			Fabric 1			Fabric 2			Aluminium Venetian			Aluminium Venetian at 45°			Fabric 1		
Day ID	Date	T_{min}	T_{max}	ΔT	$S_{glaz, min}$	$S_{glaz, max}$	ΔS	$S_{glaz, min}$	$S_{glaz, max}$	ΔS	$S_{glaz, min}$	$S_{glaz, max}$	ΔS	$S_{glaz, min}$	$S_{glaz, max}$	ΔS	$S_{glaz, min}$	$S_{glaz, max}$	ΔS	$S_{glaz, min}$	$S_{glaz, max}$	ΔS	$S_{glaz, min}$	$S_{glaz, max}$	ΔS	$S_{glaz, min}$	$S_{glaz, max}$	ΔS
1	24.08.16	22.4	34.2	11.8	25.4	42.2	16.8	25.4	49.3	23.9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	25.08.16	22.5	31.1	8.6	24.2	36.2	12.0	23.7	42.1	18.4	-	-	-	25.0	44.2	19.2	-	-	-	25.7	28.3	2.6	-	-	-	-	-	-
3	26.08.16	20.8	27.9	7.1	24.7	42.0	17.3	24.4	50.5	26.1	-	-	-	23.5	51.5	28.0	-	-	-	-	-	-	24.9	29.3	4.4	-	-	-
4	30.08.16	17.3	28.3	11.0	24.5	41.3	16.8	23.8	49.5	25.7	-	-	-	22.1	50.3	28.2	-	-	-	-	-	-	23.9	28.7	4.8	-	-	-
5	01.09.16	16.7	28.4	11.7	25.1	40.4	15.3	23.5	48.4	24.9	-	-	-	-	-	-	20.3	50.9	30.6	-	-	-	-	-	-	24.1	29.7	5.6
6	08.09.16	19.7	25.5	5.8	24.2	36.6	12.4	24.1	43.8	19.7	24.3	41.2	16.9	-	-	-	24.2	45.4	21.2	-	-	-	-	-	-	-	-	-
7	28.09.16	14.3	23.2	8.9	19.5	34.1	14.6	18.3	41.2	22.9	-	-	-	19.4	45.9	26.5	18.6	41.9	23.3	-	-	-	-	-	-	-	-	-
8	29.09.16	16.9	20.4	3.5	21.2	29.9	8.7	-	-	-	-	-	-	-	-	-	21.0	34.8	13.8	20.8	24.0	3.2	-	-	-	21.7	24.2	2.5
9	30.09.16	13.2	20.1	6.9	19.5	34.7	15.2	-	-	-	-	-	-	-	-	-	17.4	41.9	24.5	18.7	21.7	3.0	-	-	-	19.4	25.7	6.3
10	03.10.16	10.5	21.4	10.9	18.6	38.5	19.9	-	-	-	-	-	-	-	-	-	15.7	48.5	32.8	17.9	22.6	4.7	-	-	-	18.3	27.1	8.8
11	05.10.16	13.0	20.5	7.5	19.7	36.2	16.5	-	-	-	19.3	41.7	22.4	-	-	-	-	-	-	18.9	22.5	3.6	-	-	-	19.3	24.8	5.5
12	06.10.16	13.5	18.7	5.2	20.1	29.0	8.9	-	-	-	18.7	30.2	11.5	-	-	-	-	-	-	18.5	22.3	3.8	-	-	-	19.1	22.7	3.6
13	11.10.16	9.9	18.2	8.3	16.7	29.2	12.5	16.2	33.7	17.5	-	-	-	16.1	33.7	17.6	-	-	-	-	-	-	17.7	21.5	3.8	-	-	-
14	12.10.16	12.3	16.4	4.1	18.1	27.8	9.7	17.4	32.7	15.3	-	-	-	17.5	34.5	17.0	-	-	-	-	-	-	18.3	21.0	2.7	-	-	-
15	13.10.16	11.1	16.0	4.9	17.7	27.1	9.4	-	-	-	17.6	29.8	12.2	16.9	31.4	14.5	-	-	-	-	-	-	17.6	20.5	2.9	-	-	-
16	14.10.16	4.5	15.3	10.8	18.3	22.0	3.7	-	-	-	17.5	22.7	5.2	17.6	23.8	6.2	-	-	-	-	-	-	18.6	19.9	1.3	-	-	-

Table 13, displays the findings from the means comparison paired t-Test of glazing surface temperatures (S_{glaz}). These indicate that in all cases there was a significant difference between the surface temperature increase of the glazing (ΔS_{glaz}) in the non-shaded room (control room) and the surface temperature increase (ΔS_{glaz}) in the internal and externally shaded rooms. Figure 22 provides a visual representation of the differences between the 95% confidence intervals for the internal and externally shaded rooms and the means of each paired sample.

Table 13. Means comparison paired t-Test of the averaged difference in Glazing Surface Temperature Increase (ΔS_{glaz}) between rooms with and without internal and external shading.

Pair	No. of Paired Samples	Mean (°C)	SD (°C)	SEM (°C)	95% Confidence Interval of Difference Lower (°C)	Upper (°C)	t - statistic (°C)	Degrees of Freedom	*p*
No Blind vs Internal Shading	16	-7.25	3.22	0.81	-8.96	-5.53	9.00	15	<0.001*
No Blind vs External Shading	13	8.86	3.31	0.91	6.87	10.86	9.67	12	<0.001*

*Level of significance, $p < 0.05$

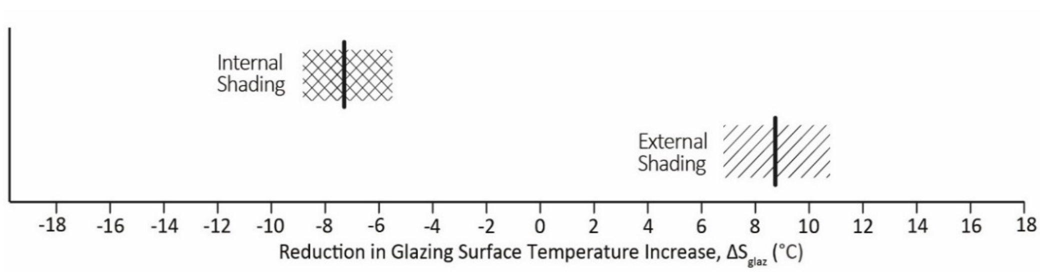

Figure 22. Mean and 95% confidence interval of the reduction in Glazing Surface Temperature Increase, ΔS_{glaz}, between rooms with and without internal and external shading.

The analysis identifies with 95% confidence that:

- Internal shading will increase the glazing surface temperature by between 5.53°C - 8.96°C. The room with internal shading would therefore have glazing surface temperatures that are 5.53°C - 8.96°C warmer than a room without shading.
- External shading will reduce the glazing surface temperature by between 6.87°C - 10.86°C. The room with external shading would therefore have glazing surface temperatures that are 6.87°C - 10.86°C cooler than a room without shading.

Table 14. Minimum Temperatures ($_{min}$), Maximum Temperatures ($_{max}$) and Temperature Increase (Δ) of External Air Temperatures (T) and Mullion Surface Temperatures ($S_{mullion}$) over 16 days between 8 am – 4 pm. The solar shading specified was fixed at a closed lowered position or a closed 45° angle for the entirety of the day.

					Mullion Temperatures ($S_{mullion}$ in °C)																							
		External Air Temperature (°C)			No Blind			Aluminium Venetian			Aluminium Venetian at 45°			Fabric 1			Fabric 2			Aluminium Venetian			Aluminium Venetian at 45°			Fabric 1		
DAY ID	Date	T_{min}	T_{max}	ΔT	$S_{mullion, min}$	$S_{mullion, max}$	$ΔS_{mullion}$	$S_{mullion, min}$	$S_{mullion, max}$	$ΔS_{mullion}$	$S_{mullion, min}$	$S_{mullion, max}$	$ΔS_{mullion}$	$S_{mullion, min}$	$S_{mullion, max}$	$ΔS_{mullion}$	$S_{mullion, min}$	$S_{mullion, max}$	$ΔS_{mullion}$	$S_{mullion, min}$	$S_{mullion, max}$	$ΔS_{mullion}$	$S_{mullion, min}$	$S_{mullion, max}$	$ΔS_{mullion}$	$S_{mullion, min}$	$S_{mullion, max}$	$ΔS_{mullion}$
1	24.08.16	22.4	34.2	11.8	23.5	48.6	25.1	21.9	54.1	32.2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	25.08.16	22.5	31.1	8.6	22.8	40.6	17.8	23.8	43.6	19.8	-	-	-	23.5	45.8	22.3	-	-	-	24.1	28.6	4.5	-	-	-	-	-	-
3	26.08.16	20.8	27.9	7.1	22.2	47.4	25.2	22.2	54.0	31.8	-	-	-	21.8	57.2	35.4	-	-	-	-	-	-	22.5	29.8	7.3	-	-	-
4	30.08.16	17.3	28.3	11.0	19.8	46.0	26.2	19.1	52.2	33.1	-	-	-	19.3	56.0	36.7	-	-	-	-	-	-	20.0	29.0	9.0	-	-	-
5	01.09.16	16.7	28.4	11.7	20.0	43.2	23.2	19.2	49.4	30.2	-	-	-	-	-	-	17.6	53.3	35.7	-	-	-	-	-	-	21.3	34.2	12.9
6	08.09.16	19.7	25.5	5.8	21.5	37.8	16.3	21.2	43.1	21.9	-	-	-	-	-	-	20.9	41.1	20.2	-	-	-	-	-	-	-	-	-
7	28.09.16	14.3	23.2	8.9	16.0	33.2	17.2	15.3	37.7	22.4	-	-	-	25.6	36.7	21.1	15.2	39.6	24.4	-	-	-	-	-	-	-	-	-
8	29.09.16	16.9	20.4	3.5	18.3	30.0	11.7	-	-	-	-	-	-	-	-	-	18.8	33.5	14.7	18.9	21.4	2.5	-	-	-	19.6	25.3	5.7
9	30.09.16	13.2	20.1	6.9	15.5	34.0	18.5	-	-	-	-	-	-	-	-	-	14.3	41.7	27.4	16.0	21.4	5.4	-	-	-	16.5	28.8	12.3
10	03.10.16	10.5	21.4	10.9	15.6	42.4	26.8	-	-	-	-	-	-	-	-	-	13.5	51.9	38.4	15.3	23.5	8.2	-	-	-	15.3	34.3	19.0
11	05.10.16	13.0	20.5	7.5	16.4	36.1	19.7	-	-	-	15.9	35.9	20.0	-	-	-	-	-	-	16.9	23.4	6.5	-	-	-	16.3	28.3	12.0
12	06.10.16	13.5	18.7	5.2	17.1	29.3	12.2	-	-	-	16.0	30.6	14.6	-	-	-	-	-	-	16.8	21.7	4.9	-	-	-	16.9	24.8	7.9
13	11.10.16	9.9	18.2	8.3	13.5	29.7	16.2	13.0	32.3	19.3	-	-	-	12.1	31.1	19.0	-	-	-	-	-	-	14.4	21.0	6.6	-	-	-
14	12.10.16	12.3	16.4	4.1	15.4	27.6	12.2	14.5	30.7	16.2	-	-	-	14.8	29.7	14.9	-	-	-	-	-	-	15.9	20.3	4.4	-	-	-
15	13.10.16	11.1	16.0	4.9	14.6	27.4	12.8	-	-	-	14.2	28.1	13.9	13.8	29.8	16.0	-	-	-	-	-	-	15.0	19.6	4.6	-	-	-
16	14.10.16	4.5	15.3	10.8	15.3	21.3	6.0	-	-	-	14.7	21.5	6.8	14.5	22.2	7.7	-	-	-	-	-	-	15.9	18.3	2.4	-	-	-

Table 15 represents the findings from the means comparison paired t-Test of mullion surface temperatures. These indicate that in all cases there was a significant difference between the surface temperature increase of the mullion ($\Delta S_{mullion}$) in the non-shaded room (control room) and the surface temperature increase ($\Delta S_{mullion}$) in the internal and externally shaded rooms. Figure 23 provides a visual representation of the differences between the 95% confidence intervals for the internal and externally shaded rooms and the means of each paired sample.

Table 15. Means Comparison Paired t-Test of the averaged difference in Mullion Surface Temperature Increase ($\Delta S_{mullion}$) between rooms with and without out internal and external shading.

					95% Confidence Interval of Difference				
Pair	No. of Paired Samples	Mean (°C)	SD (°C)	SEM (°C)	Lower (°C)	Upper (°C)	t - statistic (°C)	Degrees of Freedom	*p*
No Blind vs Internal Shading	16	-5.14	3.44	0.86	-6.98	-3.31	5.98	15	<0.001*
No Blind vs External Shading	13	10.35	4.15	1.15	7.85	12.86	9.00	12	<0.001*

*Level of significance, $p < 0.05$

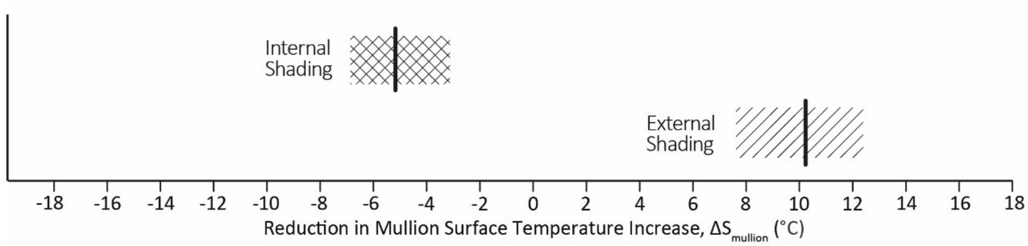

Figure 23. Mean and 95% confidence interval of the reduction in Mullion Surface Temperature Increase, $\Delta S_{mullion}$, between rooms with and without internal and external shading.

The analysis identifies with 95% confidence that:

- Internal shading will increase the mullion surface temperature by between 3.31°C - 6.98°C. The room with internal shading would therefore have mullion surface temperatures that are 3.31°C - 6.98°C warmer than a room without shading.
- External shading will reduce the mullion surface temperature by between 7.85°C - 12.86°C. The room with external shading would therefore have mullion surface temperatures that are 7.85°C - 12.86°C cooler than a room without shading.

3.5.5 Acoustic Data

Over the 4 days when data was collected the noise experienced within the room with windows open resulted in a night-time (11 pm – 7 am) noise level of 73 dB L_{Amax} and a 60 dB $L_{Aeq.}$ During the day, the L_{Aeq} was 61 dB. Whilst the façade with windows open still attenuated the external noise levels from 95 dB L_{Amax} and a 65 dB L_{Aeq} at night and 67 dB L_{Aeq} during the day (soundplanning, 2014) the internal noise levels were still substantially above the recommended 30 dB L_{Aeq} for bedrooms (CIBSE, 2015).

3.6 Case Study 2 Results

3.6.1 External Weather Conditions

Over the 26 days where internal operative temperatures were used in analysis the maximum external air temperatures (T_{max}) exceeded 25°C on five days between 8 am and 4 pm, on fifteen days T_{max} remained between 20 - 25°C and for 6 days the T_{max} were between 15 - 20°C. External wind velocities were considered normal during all days of data collection.

3.6.2 CIBSE TM52: Frequency and Severity of Overheating with and without Internal Shading

Criterion 1: Number of Overheating Hours

Figure 24 presents the monitored hourly averaged operative temperatures (Θ_{1hr}) for the control room (without shading) and the test room (with shading) which are plotted against the exponentially weighted daily mean external air temperature (T_{rm})[21]. The calculated Θ_{max} (dashed lines) and Θ_{upp} (red line) are also given in Figure 24 the former represents the maximum acceptable operative temperature as per BS EN 15251 (BSI, 2015)[22] and the latter represents the absolute maximum daily temperature according to Criterion 2. In this case study we have reviewed the criteria against Category I and Category III thresholds[23]. Each scatter plot on the graph that exceeds the Θ_{max} limit by 1°C represents 1 hour of overheating as per Criterion 1. Daily temperature profiles are provided in Figure 25 - 28 for each of the days monitored. These figures compare the non shaded room with the internally shaded room. The daily temperature profiles identify the increase in the hourly

[21] T_{rm} considers the mean outdoor air temperature of the previous seven days and applies a heavier weighting to the days closest to the day in question, see Equation 4 (p. 75).
[22] CIBSE TM52 definition of Θ_{max} is derived from the exponentially weighted running mean outdoor air temperature (T_{rm}) and the suggested acceptable temperature range that occupants can tolerate (K), see Equation 3 & 4 (p. 75).
[23] Category I refers to occupancy by fragile and vulnerable persons and Category III refers to the moderate expectation of existing buildings, see Table 7 (p. 76).

averaged internal operative temperature (Θ_{1hr}), the external air temperature (T_{1hr}) throughout the day, and the calculated T_{rm}, Θ_{max}, and Θ_{upp}.

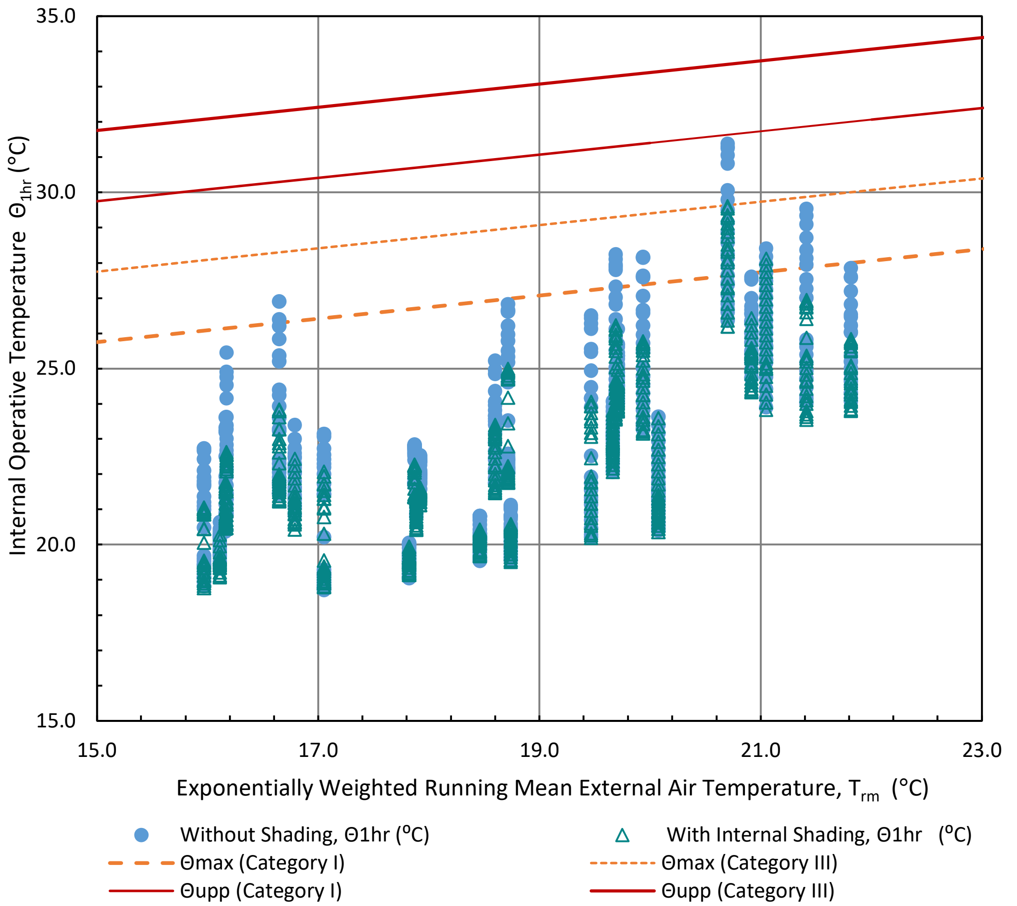

Figure 24. Scatter plot of hourly averaged indoor operative temperature (Θ_{1hr}) plotted against the exponentially weighted running mean external air temperature (T_{rm}) with plots relating to rooms with no shading (●) and rooms with internal shading (Δ) (624 monitored readings).

No Shading vs Internal Shading (Category I)

- When the rooms without shading were evaluated 2.2% of the hours were equal to or exceeded the Θ_{max} by 1°C, which is equivalent to 14 hours of the total 624 hours monitored.
- When the rooms were internally shaded 1.3% of the hours were equal to or exceeded the Θ_{max} by 1°C, which is equivalent to 8 hours of the total 624 hours monitored.

No Shading vs Internal Shading (Category III)

- When the rooms without shading were evaluated 0.8% of the hours were equal to or exceeded the Θ_{max} by 1°C, which is equivalent to 5 hours of the total 624 hours monitored.
- When the rooms were internally shaded operative temperatures did not equal or exceed the Θ_{max} threshold.

Criterion 1 was passed when rooms had no shading and internal shading installed for both Category I and III occupants.

The percentage reduction in the number of hours that exceeded the Θ_{max} by 1°C between the non-shaded room and the internally shaded room identifies that the presence of internal shading reduced the number of hours by approximately 43% for Category I occupancy and 100% for Category III occupancy.

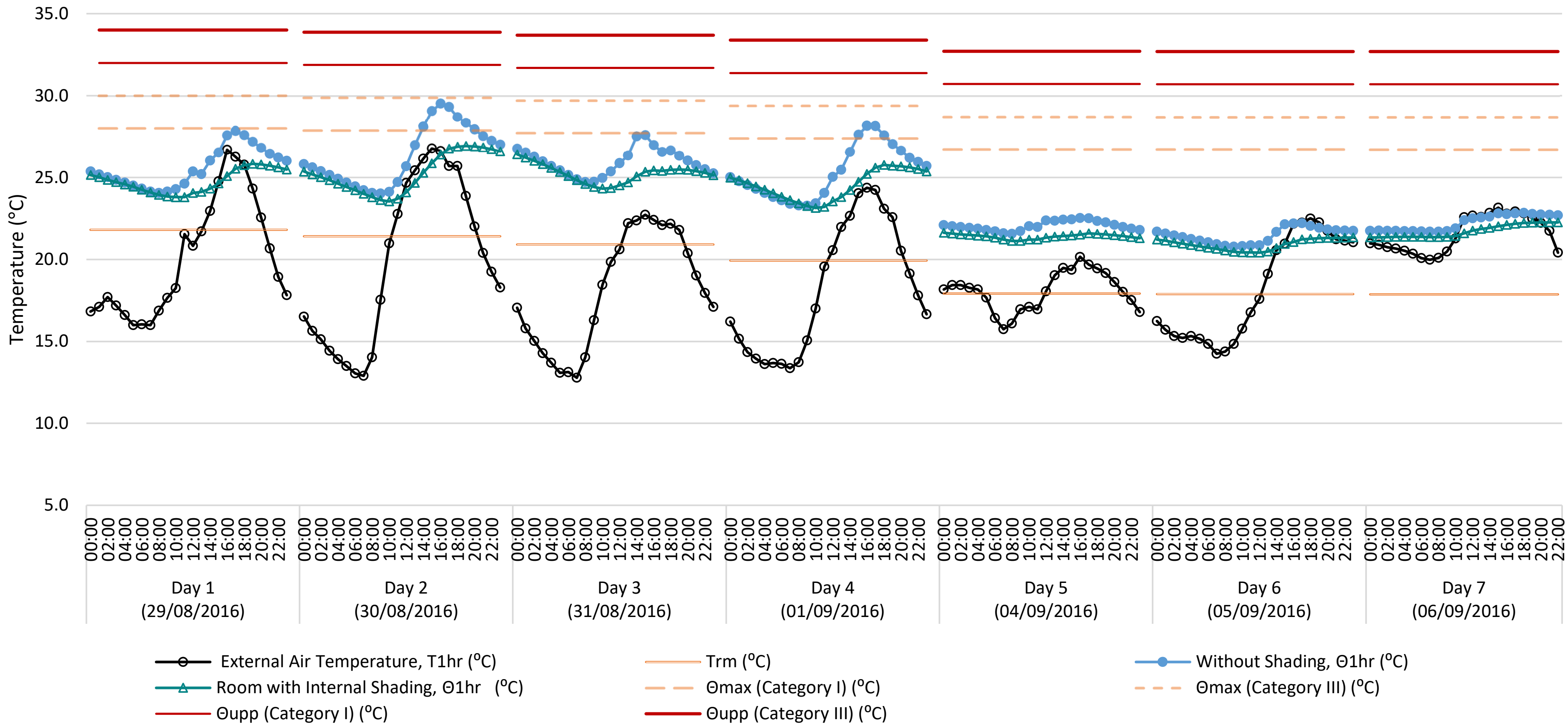

Figure 25. Daily temperature profiles comparing the measured hourly average external air temperature (○), internal operative temperature for rooms with (Δ) and without internal shading (●), the exponentially weighted running mean air temperature (T_{rm}), the internal maximum acceptable operative temperature (Θ_{max}) and absolute maximum operative temperature (Θ_{upp}) for the days monitored in August and September 2016 (Graph 1 of 4).

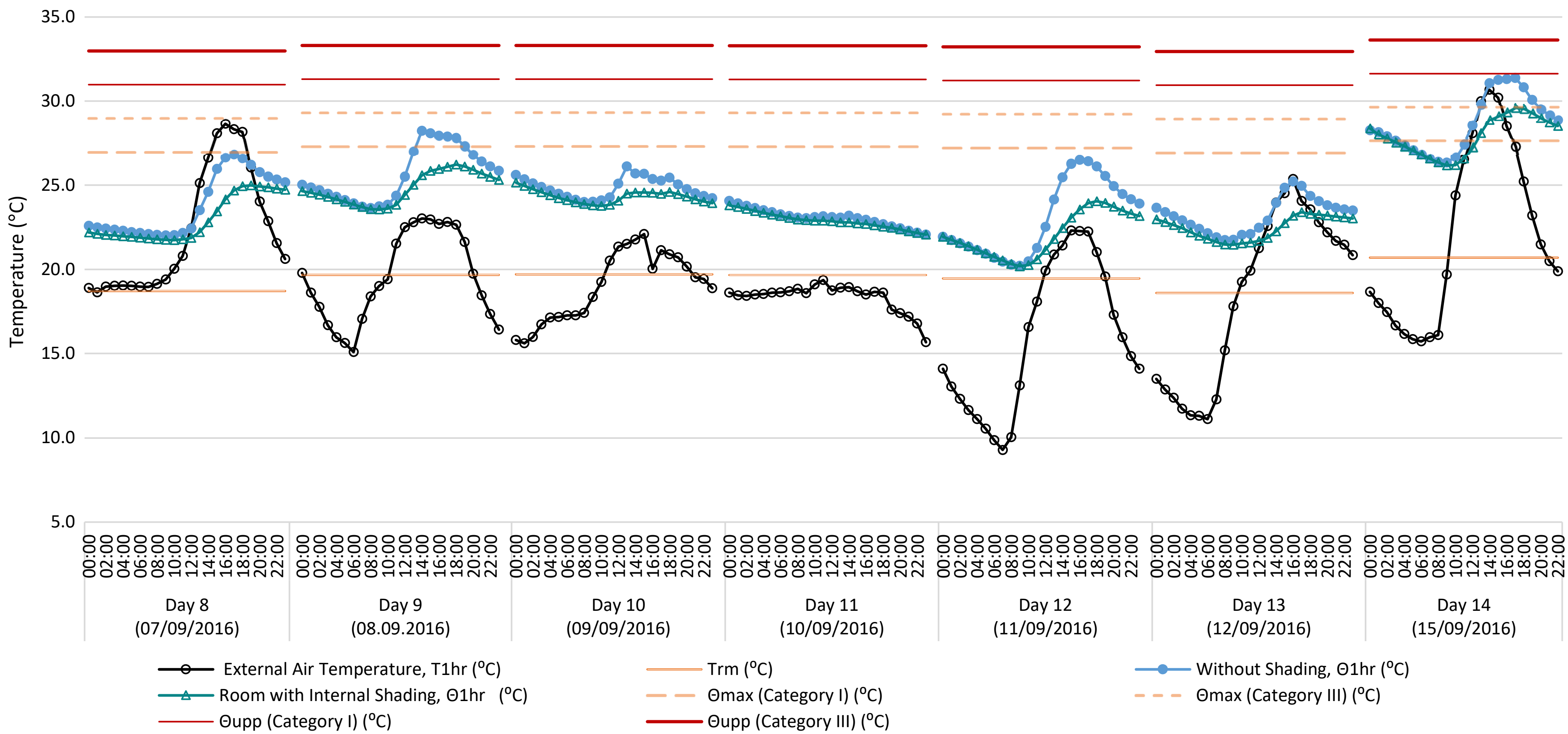

Figure 26. Daily temperature profiles comparing the measured hourly average external air temperature (○), internal operative temperature for rooms with (Δ) and without internal shading (●), the exponentially weighted running mean air temperature (T_{rm}), the internal maximum acceptable operative temperature (Θ_{max}) and the absolute maximum operative temperature (Θ_{upp}) for the days monitored in September 2016 (Graph 2 of 4).

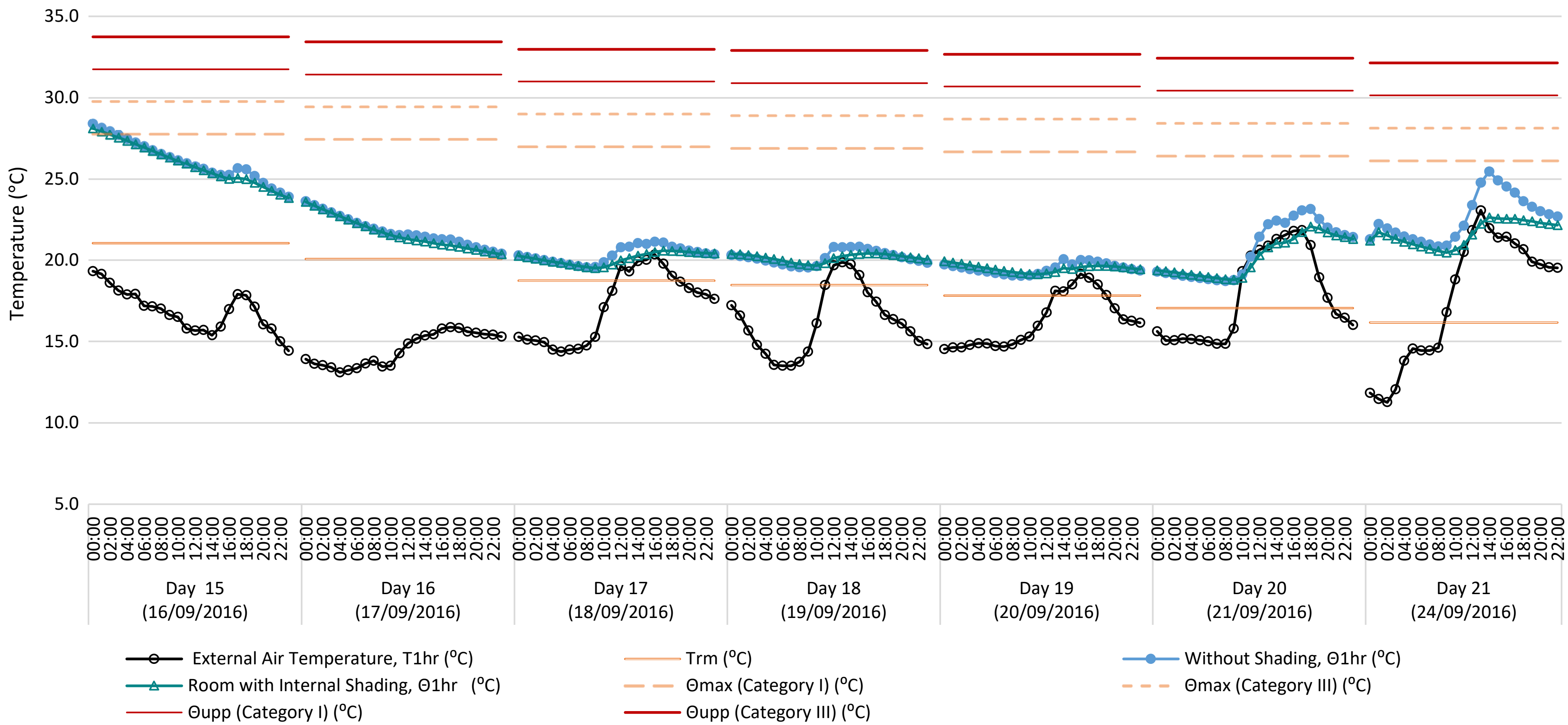

Figure 27. Daily temperature profiles comparing the measured hourly average external air temperature (○), internal operative temperature for rooms with (Δ) and without internal shading (●), the exponentially weighted running mean air temperature (T_{rm}), the internal maximum acceptable operative temperature (Θ_{max}) and the the absolute maximum operative temperature (Θ_{upp}) for the days monitored in September 2016 (Graph 3 of 4).

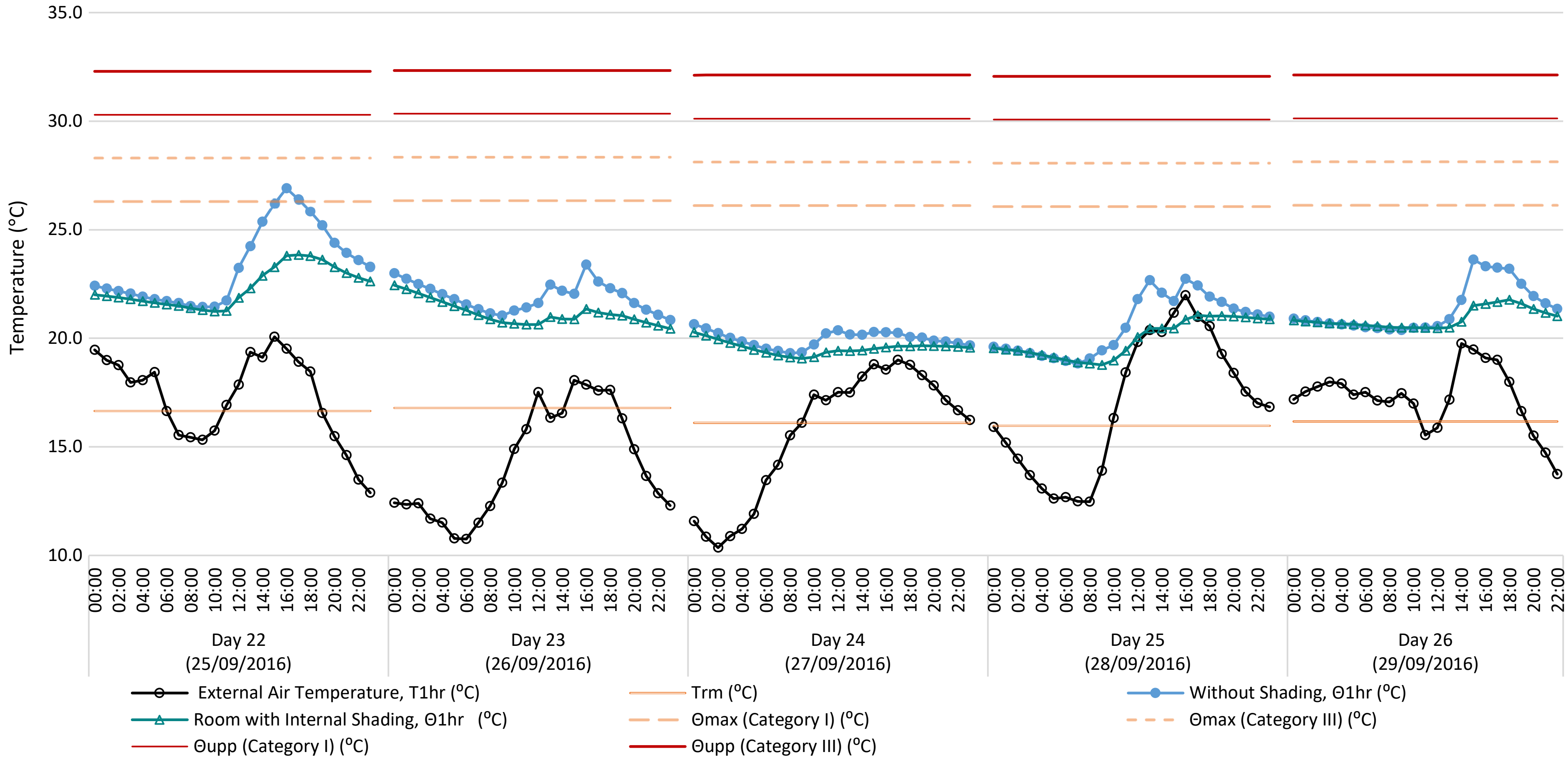

Figure 28. Daily temperature profiles comparing the measured hourly average external air temperature (○), internal operative temperature for rooms with (Δ) and without internal shading (●), the exponentially weighted running mean air temperature (T_{rm}), the internal maximum acceptable operative temperature (Θ_{max}) and the absolute maximum operative temperature (Θ_{upp}) for the days monitored in September 2016 (Graph 4 of 4).

Criterion 2: Daily Weighted Exceedance

The individual days monitored and scenarios where internal shading was used in rooms were reviewed. The weighted exceedance (W_ε) was calculated in relation to Equation 5 (p. 76) for each day monitored with either no shading or internal shading in use.

No Shading

- The recommended W_ε limit was exceeded on 1 of the 26 days monitored when there was no blind.

Internal Shading

- The recommended W_ε limit was not exceeded on any of the 26 days when internal blinds were closed.

Criterion 2 was not met when the room had no internal shading, but the criterion was passed when the test room had internal shading extended.

Criterion 3: Absolute Maximum Daily Temperature

Figure 24 also presents the absolute maximum temperature that should be experienced within a day termed Θ_{upp} for both Category I and Category III. The Θ_{upp} was not exceeded and therefore Criterion 3 was passed when internal shading was closed and when no shading device was used across the 26 days.

3.6.3 CIBSE TM59: Night-time overheating with and without Internal Shading

Θ_{1hr} with and without a shading device were reviewed between the hours of 10 pm and 7 am for those hours that exceeded 26°C.

No Shading

- When rooms with no shading were reviewed 21 hours exceeded the 26°C threshold of the 234 monitored hours.

Internal Shading

- When rooms with internal shading were reviewed 20 hours exceeded the 26°C threshold of the 234 monitored hours.

This suggests that the room with internal shading was more effective at reducing overheating risk at night than the room without shading.

3.6.4 Mitigation of Daily Operative Temperature Increase

The temperature increase in internal operative temperature, ΔΘ, and external air temperature, ΔT, were calculated in °C for each testing scenario. The Δ for each blind type tested are presented in Table 17 and were used in the inferential statistics carried out.

Table 16 represent the findings from the paired t-Test of operative temperatures. A significant difference was found between the operative temperature increase (ΔΘ) in the non-shaded room (control room) and the operative temperature increase (ΔΘ) in the room with internal shading.

Table 16. Means Comparison Paired t-Test of the averaged difference in Operative Temperature Increase (ΔΘ) between rooms with and without internal shading.

					95% Confidence Interval of Difference				
Pair	No. of Paired Samples	Mean (°C)	SD (°C)	SEM (°C)	Lower (°C)	Upper (°C)	t - statistic (°C)	Degrees of Freedom	*p*
No Blind vs Internal Shading	26	1.28	.86	0.17	0.94	1.64	7.62	25	<0.001*

*Level of significance, $p < 0.05$

The analysis identifies with 95% confidence that:

- Internal shading reduced the operative temperature increase by between 0.94°C - 1.64°C. The room with internal shading would therefore be 0.94°C - 1.64°C cooler than a room without shading.

Table 17. Minimum (min), Maximum (max) and the Temperature Increase (Δ) of the External Air Temperatures (T) and Internal Operative Temperatures (Θ) over the 26 days monitored. The solar shading specified was fixed at a closed lowered position for the entirety of the day.

		External Air Temperature (°C)			Internal Operative Temperature (°C)														
					No Blind			Internal Blinds											
								Honeycomb Cellular			Aluminium Venetian			Wooden Venetian			Dim-out Fabric Roller		
Day ID	**Date**	T_{min}	T_{max}	ΔT	Θ_{min}	Θ_{max}	ΔΘ	Θ_{min}	Θ_{max}	ΔΘ	Θ_{min}	Θ_{max}	ΔΘ	Θ_{min}	Θ_{max}	ΔΘ	Θ_{min}	Θ_{max}	ΔΘ
1	29.08.2016	15.9	26.7	10.8	24.1	28.0	3.9	23.8	25.8	2.1	-	-	-	-	-	-	-	-	-
2	30.08.2016	12.9	26.9	14.0	24.0	29.6	5.5	23.5	26.9	3.4	-	-	-	-	-	-	-	-	-
3	31.08.2016	12.8	22.9	10.1	24.7	27.8	3.1	24.3	26.3	2.0	-	-	-	-	-	-	-	-	-
4	01.09.2016	13.3	24.4	11.0	23.3	28.2	5.0	23.1	25.8	2.6	-	-	-	-	-	-	-	-	-
5	04.09.2016	15.8	20.2	4.4	21.5	22.6	1.1	-	-	-	21.1	21.6	0.5	-	-	-	-	-	-
6	05.09.2016	14.2	22.5	8.3	20.8	22.5	1.7	-	-	-	20.4	21.3	0.9	-	-	-	-	-	-
7	06.09.2016	19.3	23.3	3.9	21.7	22.8	1.2	-	-	-	21.3	22.3	0.9	-	-	-	-	-	-
8	07.09.2016	18.6	28.7	10.0	22.0	26.8	4.8	-	-	-	21.7	25.0	3.3	-	-	-	-	-	-
9	08.09.2016	15.1	23.2	8.1	23.6	28.5	4.9	-	-	-	23.5	26.2	2.7	-	-	-	-	-	-
10	09.09.2016	15.6	22.1	6.5	24.0	26.4	2.4	-	-	-	23.8	25.0	1.2	-	-	-	-	-	-
11	10.09.2016	14.9	19.4	4.4	21.9	24.0	2.1	-	-	-	21.9	23.7	1.8	-	-	-	-	-	-
12	11.09.2016	9.2	22.3	13.1	20.2	26.5	6.3	-	-	-	20.2	24.1	3.9	-	-	-	-	-	-
13	12.09.2016	11.1	25.4	14.3	21.7	25.3	3.5	-	-	-	21.5	23.4	1.9				-	-	-
14	15.09.2016	15.7	30.8	15.0	26.3	31.6	5.2	-	-	-	-	-	-	26.1	29.7	3.5	-	-	-
15	16.09.2016	14.2	19.3	5.2	23.6	28.2	4.7	-	-	-	-	-	-	23.5	28.0	4.4	-	-	-
16	17.09.2016	13.1	15.9	2.8	20.3	23.5	3.2	-	-	-	-	-	-	20.2	23.4	3.2	-	-	-
17	18.09.2016	14.4	20.3	6.0	19.6	21.2	1.7	-	-	-	-	-	-	19.5	20.6	1.1	-	-	-
18	19.09.2016	13.5	20.0	6.5	19.5	21.0	1.4	-	-	-	-	-	-	19.7	20.4	0.8	-	-	-
19	20.09.2016	14.5	19.2	4.7	19.0	20.2	1.2	-	-	-	-	-	-	19.1	19.9	0.8	-	-	-
20	21.09.2016	14.7	21.9	7.1	18.7	23.2	4.5	-	-	-	-	-	-	18.8	22.1	3.3	-	-	-
21	24.09.2016	11.3	23.1	11.8	20.8	25.5	4.7	-	-	-	-	-	-	-	-	-	20.5	22.6	2.2
22	25.09.2016	12.6	20.1	7.5	21.4	26.9	5.5	-	-	-	-	-	-	-	-	-	21.2	23.9	2.6
23	26.09.2016	10.7	18.2	7.5	20.6	23.6	3.0	-	-	-	-	-	-	-	-	-	20.2	22.3	2.1
24	27.09.2016	10.3	19.0	8.7	19.3	20.5	1.2	-	-	-	-	-	-	-	-	-	19.1	20.2	1.1
25	28.09.2016	12.4	22.0	9.5	18.8	23.0	4.2	-	-	-	-	-	-	-	-	-	18.8	21.1	2.3
26	29.09.2016	12.8	20.0	7.2	20.4	23.8	3.4	-	-	-	-	-	-	-	-	-	20.4	21.8	1.3

3.7 Discussion

Within Case Study 1 external shading combined with night-time ventilation was most efficient at reducing overheating risk when assessed against CIBSE TM52. External shading reduced the internal operative temperature increase, $\Delta\Theta_{,}$ by 11 - 18°C. Internal shading was less effective in preventing overheating risk, but it was still able to achieve 73% of the operative temperature reduction that was provided when external shading was used.

The Criterion 1 assessment for Case Study 1 identified that:

- When internal shading was used the number of overheating hours were reduced by 62.5% - 72% when compared to a room without shading.
- When external shading was used the number of overheating hours were reduced by 96% - 100% when compared to a room without shading.

The impact of internal and external shading varies with the number of overheating hours dependant on the suggested comfort ranges (Category I or II). Extending external shading during the day and opening windows at night meant that the rooms assessed were no longer considered likely to overheat when considering non-vulnerable occupants. However, when either no shading, internal shading or external shading was assessed in relation to vulnerable occupants, additional cooling strategies would need to be incorporated to prevent the building from overheating. Considering these measurements were taken in 2016 it is likely in years to come, as external temperatures increase and warmer weather events become more frequent, active cooling will be required to achieve thermal comfort within this building design. Whilst this may be the case, the amount of active cooling required to maintain comfortable temperatures will be significantly less if external or internal shading is implemented in combination with night-time ventilation. This finding is supported by prior research literature relating to the energy saving potential of shading devices (Comfort without air-conditioning in refurbished offies - an assessment of possibilites, no date; ES-SO, 2014; Hutchins, 2015; Seguro and Palmer, 2016). The results also show that the severity of the overheating (for both vulnerable and non-vulnerable occupants) reduced to a level to comply with Criteria 2 and 3 of TM52 when both internal and external shading were extended.

Case Study 1 examined the risk of overheating in summer months, August, and September, when overheating is more likely to occur. It also evaluated overheating in October, when overheating is generally believed to occur less. Interestingly overheating events occurred in all three months despite the external air temperatures cooling considerably in October. The overheating that occurred in October are felt to have occurred because of the altitude of the sun which meant that a greater amount of low angle solar radiation entered the building for a longer duration of time during the day. This supports the research of Morgan et al*.* (2017) who also identified overheating in winter months but was unable to detect the specific reasons because of the difficulties in monitoring occupant behaviour. Shading devices positioned vertical to the window (e.g., roller blinds, venetian blinds, shutters) can mitigate low angle solar gains where shading strategies that protrude horizontally from the façade (e.g., awnings, canopies, brise soleil) are less able to protect buildings from low angle solar gain received between autumn and spring. This finding suggests that in certain buildings evaluations of overheating should also assess mid-season months, particularly for those buildings that are more likely to overheat because of increased solar gains (e.g., buildings with large, glazed facades).

Data relating to the internal surface temperatures of the window system found significant differences between rooms with and without internal and external shading. External shading not only reduced the amount of solar gain entering the building, but it also prevented the surface temperatures of the window system from increasing. However, extending internal shading increased the surface temperatures of the glazing and mullions. The difference between internal and external shading systems on the glazing and mullion surface temperatures is related to the difference in installation position and the thermal properties of the shading products. Even though internal shading increased the surface temperatures of the glazing system this did not offset the number of overheating hours or the severity of the overheating. This data correlates with previous research conducted by Bessoudo et al*.* (2010) who also found that internal shading increased glazing surface temperatures.

Within Case Study 2, two of the three CIBSE TM52 criteria were passed when the rooms were not shaded and all the criteria when the rooms had internal shading extended. Criterion 2 was failed when the room had no shading. This supports Case Study 1s finding that internal shading reduces the severity of overheating. Whilst Criterion 1 was passed despite the position of the internal shading product, the reduction in overheating hours identifies that internal shading provided a 43 - 100% reduction in the number of overheating hours experienced.

When Case Study 2 was evaluated for night-time overheating the room with internal shading overheated slightly less (by 1 hour) than the non-shaded room. However, the internal temperatures in the room with internal shading still exceeded the 26°C overheating threshold for 8.5 % (20 hours) of the 234 hours monitored. This suggests that the mitigation strategy of internal shading alone was not effective in eliminating overheating at night. It is likely that additional factors contributed to the overheating experienced at night such as the internal heat gains contributed by occupants (i.e., electricity usage, hot water, and occupants) and the thermal inertia of the building. Solar gains that entered other rooms in the building (that were not being monitored) would have been absorbed by the thermal mass of the building and re-radiated within the building as heat when external temperatures started to reduce at night. With windows closed in the monitored rooms this heat would have built up within the rooms and caused internal temperatures to increase. Considering windows were not opened at night in the Case Study 2 building and internal thermal loads and occupant behaviour within the house were not monitored, we are unable to confirm if this was why there was little difference between the rooms in night-time temperatures.

The inferential statistics found that the use of internal shading within Case Study 2 reduced the internal operative temperature increase, $\Delta\Theta_{,}$ by 1 - 2°C. This is significantly less than the outcome of Case Study 1, 9 - 13°C. It is difficult to draw comparisons between the two case studies as the buildings differed in location and orientation, design, internal heat gains and the weather conditions experienced during the monitoring period. However, it is worth noting that the differences in façade design and the overall design of the building likely contributed a significant amount to this temperature difference. The two case study buildings had very different glazing to wall ratios (GWR) - in Case Study 1 the GWR was 65% and in Case Study 2 was 26%. Furthermore, the Case Study 1 building had a single aspect design (windows only on one side of the building), had a low thermal mass structural design, was located in an urban area (and so subject to the urban heat island effect), and the window opening areas were relatively small when compared to the overall area of the window. In modern methods of building design larger window areas are preferred as they allow more natural daylight into buildings which can subsequently improve visual comfort and help reduce electric lighting energy consumption (Seguro and Palmer, 2016). Case Study 1 highlights the importance of integrating suitable shading strategies when designing heavily glazed façades within building design.

Frequently night-time ventilation is not feasible in mitigating overheating because it compromises acoustic comfort. Within Case Study 1 the acoustic measures imply that keeping windows fully open at night (for night-time ventilation) would subsequently cause sleep disturbances for occupants. Sleep disturbances at night are detrimental for health and well-being and can negatively affect productivity. Hafner et al. (2016) identifies that if an individual obtains only 6 - 7 hours' sleep as opposed to 7 - 9 hours' sleep work activity will deteriorate by 1.47%. When an individual obtains < 6 hours sleep working activity will deteriorate by 2.36%. This deterioration can also be linked to an economic cost (MHCLG, 2019c).

Lastly night-time ventilation was not adequate in reducing the internal operative temperatures within the recommended comfort levels alone in Case Study 1. On three of the sixteen days monitored the initial operative temperature, recorded at 8 am, in the control room (without shading) exceeded 26^{o}C. It is believed by the researcher that this is due to the small area of opening and the inability to cross-ventilate the rooms. If the initial operative temperatures were lower from the provision of night-time ventilation, then external shading and night-time ventilation may have been able to maintain temperatures within the comfort threshold throughout the day.

3.8 Summary

Solar shading combined with night-time ventilation significantly reduced the risk of overheating by minimising the increase in operative temperature throughout the day. The reduction in operative temperatures was obtained by the shading obstructing solar gains from entering the building and contributing to the increase in internal temperatures.

When comparing internal and external shading strategies, external shading was most effective in reducing operative temperature increase and overheating risk when assessed against the recommended industry standard (CIBSE TM52). Nevertheless, the use of internal shading meant that two of the three criteria were passed. The Case Study 1 building demonstrated that internal shading could achieve as much as 73% of the operative temperature reduction that external shading systems can achieve when used in a highly glazed, south-west facing apartment.

In Case Study 1 internal shading significantly reduced internal operative temperature increase by almost 13°C when compared with a room without a shading product. Rooms with external shading reduced temperatures by almost 18°C when compared to a room without a shading product. However, the Case Study 2 building identified a lower reduction in operative temperature of between 1 and 2°C provided by internal shading. Whilst the temperature reduction provided by internal shading was lower in Case Study 2 than in Case Study 1 the overall overheating risk was also significantly lower in the Case Study 2 building than in the Case Study 1 building.

When assessing the number of overheating hours using the CIBSE TM52 methodology the reduction provided by shading ranged between 43% and 100% across the two case studies, depending on the suggested comfort range (Category I, II or III). In Case study 1 external shading combined with night-time ventilation reduced overheating hours by 96% (Category I) and 100% (Category II), internal shading with night-time ventilation by 62.5% (Category I) and 72% (Category II), and in Case Study 2 internal shading reduced the number of overheating hours by 43% (Category I), and 100% (Category III).

External shading not only reduced solar heat gain from entering the building more effectively than internal shading, but it also reduced the surface temperatures of the window system where internal shading was found to increase surface temperatures. The differences between the impact of each shading system on the building fabric surface temperatures contributes to the differences in its effectiveness at reducing internal operative temperatures. If air conditioning or active cooling were provided to improve the thermal comfort of occupants in the buildings the temperature reductions achieved could reduce the cooling load required providing a social, economic, and environmental benefit to occupants within domestic homes.

Night-time ventilation is a recommended method for reducing internal temperatures at night for the subsequent day. However, the acoustic measures recorded within Case Study 1 identify that in a real-world scenario if occupants opened windows at night, they would experience acoustic discomfort. Therefore, occupants would be less likely to open windows at night or would have to make a choice between prioritising their thermal comfort or their acoustic comfort. However, both scenarios can lead to poor sleep quality at night.

It is important to note that the specifics of the building design contributed to the effectiveness of the shading system as the design of the building in Case Study 1 exacerbated the risk of overheating via solar gains. The Case Study 2 building passed CIBSE TM52 Overheating Risk Assessment whether internal shading was or was not present. However, one of the criteria assessed was only passable when internal shading was in position and for all the criteria assessed the use of internal shading products meant that the criteria were more easily passed. In some cases, reducing the number of overheating hours by almost half. Internal shading in this study was found to have little effect on night-time temperatures, suggesting that internal shading alone is not sufficient in reducing overly warm night-time conditions.

CHAPTER 4. COMFORT, HEALTH, WELL-BEING & PRODUCTIVITY

4.1 Overview

Within this chapter, the aim was to assess how the position of the internal shading products affected the internal environmental conditions, in addition to the occupants' perception of the indoor environment, their health and well-being, and their subjective and objective productivity. The evaluations of occupant comfort and perceived health and well-being were well-established through the Post Occupancy Evaluation (POEs) and Sick Building Syndrome (SBS) surveys. The improvement in staff productivity is considered to be a leading driver for commercial companies in the design of healthier and more efficient (energy and operation) buildings. However, it is acknowledged that there are many different variables that impact on a person's actual productivity and only some of these are related to the internal environmental conditions within a workspace. This makes evidencing the improvements in productivity complex and problematic as many of the variables that influence an occupants' actual productivity level are difficult to measure or quantify robustly.

The effect that blinds have on the occupants and the indoor environment can also vary depending on the type of shading product in use, the position of the product (i.e., retracted or extended), and the external weather conditions. This study has been simplified to consider the impact of internal roller blinds in both open (retracted) and closed (extended) positions in a warmer weather period (i.e., summer). Nineteen employees who worked in two almost identical offices were recruited and both offices were placed in one of the two interventions. The intervention was placed on the office alternated between the test sessions. During the test session, the participants were asked to complete a test battery (a series of tests and questionnaires) twice a week over a two-month period. Qualitative and quantitative data was collected which included the following:

- Internal and external objective environment data.
- Subjective perceptions of the internal environment.
- Subjective perceptions of comfort, health, and well-being.
- Subjective and objective productivity data.

The test battery incorporated subjective questions replicating some of those used in POEs and academic research to identify the differences in the occupants' perceptions of comfort, health and well-being. The questions used in this study were tailored to focus on aspects that were most likely to vary through the altering of the position of the blinds (e.g., thermal and visual comfort). The test battery also incorporated work-type tests (e.g., text typing and grammatical reasoning) and cognitive function tests as the indicators of objective productivity.

Statistical analysis techniques were then used to assess the data in its entirety to identify the relationships between blind position and the internal objective environment conditions, as well as how these variations subsequently affected the participants' perception of the environment and objective productivity. The data collected in the two interventions (blinds open and blinds closed) was also compared between the two 'groups' of participants and then between the 'individuals' responses. Furthermore, analysis was carried out to see whether there were any trends in the way that the participants responded when the blinds were either opened or closed.

The previous literature that assesses the impact of indoor environment conditions on occupant perceptions of the internal environment, comfort, health, well-being, and productivity suggests that shading devices are likely to both positively and negatively affect the occupants. This is because when shading devices are extended in warmer weather, they simultaneously reduce the illuminance levels, limit views to the outside, and reduce internal temperatures. Cooler temperatures are associated with a positive impact in warmer weather conditions. However, experiences of low illuminance levels and limited views out are believed to have a negative effect on occupants.

In the absence of any study that has investigated how shading products affect occupant comfort, health, well-being, and productivity, the testing methodology was based on the previous research methods that are used to evaluate how perceptions and objective measures of visual and thermal comfort affect these variables. Even though the testing methods were largely based on existing methods, the intervention (i.e., the position of the blinds) was novel. The effectiveness of the methods used was assessed through a semi-structured focus group once all the data was collected. The limitations of this study are that it only assessed one form of building typology (a naturally ventilated office) during a warmer weather period. Only the impact of one type of blind (an internal screen fabric roller blind) when either opened or closed was investigated using a relatively small number of participants. Nevertheless, the population and building tested is felt to be representative of office workers in naturally ventilated buildings in the UK.

4.2 Measuring Comfort, Health, Well-being, and Productivity

The methods used to assess occupant comfort, health, well-being, and productivity were briefly discussed in Chapter 2, Section 2.5 Productivity, Health, Well-being, and Comfort (p. 9). In summary, the studies are either conducted within the field or within laboratory settings. Sometimes a mix of the two approaches is used. However, the results from the field studies are considered to have more relevance to real-world conditions (CIBSE, 2015; Seppänen et al*.,* 2006). Objective environmental data and occupant perceptions are measured consistently which are then correlated with either objective or subjective measures of comfort, health, well-being, and productivity that are collected periodically from the occupants to produce a triangulated dataset of results. This is considered to provide corroborative evidence (Lan and Lian, 2009; Al Horr et al., 2016; BCO, 2016). The mean responses and regression analysis are then used to identify how the varying environmental conditions affect the occupant responses and performance (Heschong Mahone Group, 2003; Lan et al., 2009). The metrics and frequency of the data collected varies depending on the hypothesis of the study. In the following sections, the metrics previously used as the measures of comfort, health, well-being, and productivity are described.

4.2.1 Comfort

Occupant comfort can be assessed using Post Occupancy Evaluations (POEs). These are more frequently carried out in non-domestic buildings. POEs form part of Voluntary Building Certification schemes such as BREEAM, the Home Quality Mark, and the WELL Standard (BRE, 2018; BREEAM, 2018; Delos Living LCC, 2016). They primarily consider the occupants' perceptions of lighting, view, temperature, air quality, and noise. Additional aspects that affect how occupants experience buildings may also be investigated such as the ergonomics of a space, space availability, biophilic design, and the local amenities available to the occupants (Clements-Croome, 2018; UKGBC, 2016; WGBC, 2014).

The Building User Survey (BUS), developed in the 1990s, is one of the most well-known surveys used to collect occupant subjective data in the UK and is used to benchmark buildings around the world (WGBC, 2014; Bunn and Marjanovic-Halburd, 2016). This survey presents a series of questions on a Likert scale which ask how occupants are affected by the indoor environment. For example, occupants are asked their opinion on 'Lighting (overall)' and occupants respond on a 1 - 7 scale with 1 representing 'Unsatisfactory' and 7 indicating 'Satisfactory' (Bunn and Marjanovic-Halburd, 2016; Useable Buildings, 2020).

4.2.2 Health and Well-being

Subjective Measures

In academic research, the Sick Building Syndrome (SBS) survey is frequently used. Additional questions are often added to the questionnaire depending on the focus of the research study (Elzeyadi, 2011; Federspiel et al., 2004; Lan et al., 2011; Wargocki, 1999; Wargocki et al., 2004). Wargocki (1999) presented the SBS survey on a Visual Analogue Scale (VAS) where both ends of the scale were labelled with two extremes of health symptoms (e.g., eyes aching and eyes not aching). A horizontal line was positioned between the two extremes with two vertical lines at either end. The participants were then asked to identify how they felt by placing a vertical line on the scale between the two extremes. The SBS survey covers both the physical and psychological aspects of health and includes 20 questions. In the case of Wargocki (1999), the survey was expanded to include symptoms of health that are primarily affected by poor air quality. SBS symptoms were significantly affected in the work of Lan et al. (2011), Wargocki (1999), and Elzeyadi (2011), when changes in thermal comfort, ventilation rates, air quality, access to daylight, and views were assessed.

Psychometric measures assessing occupant mood (Lan et al., 2011), fatigue (Tanabe and Nishihara, 2004), and mental workload (Lan et al., 2011) have also been used as measures of health and well-being. The presentation and assessment of these measures varies between the metrics. Lan et al. (2011) investigated the effects of thermal discomfort on occupants by using the Profile of Mood States Short Form (POMS-SF). This presents mood states (anger, depression, tension, vigour, fatigue, and confusion) on a 5-point Likert scale ranging from 0 (not at all) to 4 (extremely). All the scores were totalled except for the vigour scores which was subtracted to provide a Total Mood Disturbance (TMD) score. Self-assessed levels of fatigue are considered in both the SBS survey and the POMS-SF however Lan et al. (2011) and Tanabe and Nishihara (2004) incorporated an additional approach to assessing fatigue. Tanabe and Nishihara (2004) assessed the impact of varying the air temperatures and humidity levels on occupant productivity in a laboratory setting. Three columns of fatigue-related symptoms, each consisting of ten symptoms, were presented to each participant. They were asked to tick off the symptoms that they felt described their level of fatigue. The number of symptoms ticked in each column was associated with a specific fatigue level which relates to a type of work activity (e.g., general fatigue, fatigue caused by mental and overnight work or fatigue caused by physical work). Lastly, the mental workload test used by Lan et al. (2011) asked the participants to describe the amount of mental and physical demand that the tasks required, including how they found the pace of the tasks and a reflection on how hard they had to work to achieve their level of performance. It also asked how much effort they felt that the tasks required and how frustrated they made them feel. The questions were presented on a 5-point Likert scale from 0 (very low) to 4 (very high).

Objective Measures

Various objective health measures such as finger skin temperature, heart rate, respiration rate, end-tidal CO_2, blood oxygen level, biomarkers in saliva (alpha-amylase and cortisol), tear film quality, and blink rate were recorded by Lan et al. (2011). Lan et al. (2011) investigated the differences in the participants' responses when they were exposed to internal temperatures of 22°C and 30°C. The numerous physiological responses differed in the two thermal conditions. Warmer temperatures were significantly correlated with increased heart, respiration rate, end-tidal CO_2, blood oxygen level, level of cortisol in saliva, and tear film quality. The participant's sleep-wake hours and activity levels were examined in the work of Boubekri et al. (2014). They asked the participants to wear a watch for two weeks that monitored these aspects and the amount of light that they were exposed to. The study concluded that the workers who had access to a window were more active, had better sleep cycles, and woke up less frequently at night.

4.2.3 Productivity

Subjective Measures

Asking occupants how productive they feel is more frequently used in POEs as a way of assessing a person's productivity level. This is because the methods used to assess a person's actual objective productivity can be obstructive to the requirements of a business. Within BUS surveys and the Leesman index assessment, subjective productivity is evaluated through a -20% to +20% scale with either end of the scale represented by the word "increased" or "decreased" (Useable Buildings, 2020). Alternative questions and scales have been used in academic work. Some studies have reviewed the relationship between the perceptions and objective productivity measures. Lan and Lian (2009) and Lan et al. (2011) asked occupants to assess their "willingness to exert effort" which was significantly related to some of the objective productivity tests also used within the studies. They found that the participants were less willing to exert effort when exposed to air temperatures of 30°C as opposed to temperatures of 22°C. Additionally, Humphreys and Nicol's (2007) measurement of self-assessed productivity had a highly significant relationship ($p < 0.001$) with participants' perception of their overall comfort. Humphreys' productivity measure asked occupants "Do you feel that at present your productivity is being affected by the quality of your work environment and if so, to what extent?" The responses were given on a -2 to +2 Likert scale with extremes of “Much higher than normal” and “Much Lower than normal”. The measure used to assess a participant’s overall comfort asked them to rate this on a 7-point Likert scale with the extremes of “Very Comfortable” and “Very Uncomfortable”.

Objective Measures

Heschong Mahone Group (2003b) used two methods to assess whether daylight affected the productivity of office workers in a real-world work environment. The first identified improvements in organisational productivity. The metrics used were based on the specific tasks carried out by 100 call centre employees. For example, the volume of calls answered, the time spent on the call, and the average time that it took to answer an incoming call. However, it was stated that the metrics are very specific to one type of worker (i.e., call centre workers) and that they would not be relevant to other types of workers. The second method presented a series of mini tests and questions to 201 office workers. The mini tests were selected to test their visual and cognitive abilities. The mini tests included a Landolt C test, a letter and number search, a working memory test (or backward number recall), and a short and long-term memory test. The Landholt C test asked the participants to identify the letter “C” in a grid of letters “O” which tested the participants’ visual acuity, visual scanning efficiency, and response time. The number search test required participants to count how many times a specific digit appeared in a grid of numbers. This tested the participant’s visual acuity, visual scanning efficiency, mental alertness, response time, and short-term memory. The working memory test presented a series of numbers and asked the participants to input the numbers presented in reverse order (i.e., 1234 would be entered as 4321). Lastly, the memory tests involved showing the participants several images and after ten minutes, they were asked to identify what images they were presented with to test their short-term memory. For the long-term memory test, they were asked to remember what images they had been presented 2 and 4 weeks after being presented with the images. The researchers recommended adjustments to the tests and that future research should consider a broader range of cognitive performance measures with less of a focus on visual acuity. Nevertheless, the study still yielded results as they identified that the experiences of glare negatively affected memory (short and long-term), working memory and performance in the number search test. Overall, they found that an occupant’s access to an external view both positively and negatively affected their cognitive abilities depending on the ability being tested.

Lan et al. (2011) tested 12 participants in a simulated office setting when exposed to air temperatures of 22°C and 30°C. Subjective and objective measures of health and productivity formed part of the study design. The tests included tasks considered typical of office work (e.g., text typing and an arithmetic test), and those that tested a range of cognitive functions (e.g., memory, logical reasoning, verbal working memory, and reaction times). The speed and accuracy of responses were calculated for each participant. The responses were then compared between the interventions and relationships between the participants' performance and their responses to the subjective questionnaires were identified. The tests used as measures of cognitive function included a grammatical reasoning test, a digit span test, a visual learning memory test, a mental arithmetic test, a Stroop test[24], and a choice reaction test. Most of these tests were also used by Lan et al. (2009) and Lan and Lian (2009). The results of this study identified that at higher temperatures, the participants typed more words at 30°C. However, they made more errors in the text typing test. Mental arithmetic, grammatical reasoning, Stroop, and reaction times were also negatively affected by the warmer temperatures (30°C).

More recently, a study conducted by Harvard University (MacNaughton et al., 2016) tested 24 participants under differing CO_2 loads and Volatile Organic Compound (VOC) concentrations. A 400 PPM increase in CO_2 negatively affected cognitive performance by 21%. A 20-cfm increase in outdoor air per person improved performance by 18% and a 500-$\mu g/m^3$ increase in Total Volatile Organic Compounds (TVOCs) was associated with a 13% decrease in cognitive function performance. Cognitive function in this case was tested by giving the participants a computer-based test designed to test the effectiveness of management-level employees through an assessment of their higher-order decision-making.

4.3 Methodology

4.3.1 Site Selection

The case study building chosen was the Clarence Centre (Figure 29). The building was situated on the London South Bank University (LSBU) Campus with the south-west façade and north-west façades running parallel to two busy main roads. The second to fourth floor of the building are primarily used as office space by LSBU Research, Enterprise, and Innovation teams. It is also home to LSBU student entrepreneurs, start-ups, and a select number of small to medium-sized enterprises (SMEs). The ground floor of the building has several meeting/function rooms in addition to the Café. One of the local SMEs is a print shop.

[24] A psychology test that provides a demonstration of cognitive interference where a delay in the reaction time of a task occurs due to a mismatch in stimuli.

Figure 29. South-west external façade of the testing offices (taken with a fisheye lens).

4.3.2 Office Selection, Overview and Layout

The third floor was identified as a suitable location to conduct the study as the offices could be divided into two groups. They were almost identical in terms of office layout and construction. The offices were orientated to the south-west (230.02^{o}) and each segmented office had two south-west facing secondary glazed windows, one north-east facing single glazed window, and a single glazed rooflight. The segmented offices were divided into two groups, specifically Office A and B as per Figure 30 and Figure 32. The two offices were separated by a communal corridor, kitchen, and store room.

Figure 30. Aerial Photograph of the Clarence Centre (Google Earth (51.49, -0.10))

Each office contained two smaller offices that had semi-partitions in place with an open doorway joining the two offices (Figure 32). The four segmented offices were of almost equal size (approx. 39.2 m^2) and had similar sized glazed areas with an average wall to window ratio of 12:1. The open-plan office spaces had similar furniture layouts consisting of desks, chairs, and metal/wooden cabinets. The walls and floors were finished and painted to the same standard – white matte paint and dark grey carpet. However, there were some differences between the furniture finishes. In Office A, the desks were finished with a dark wood laminate whereas Office B desks were finished with a white top (Figure 31).

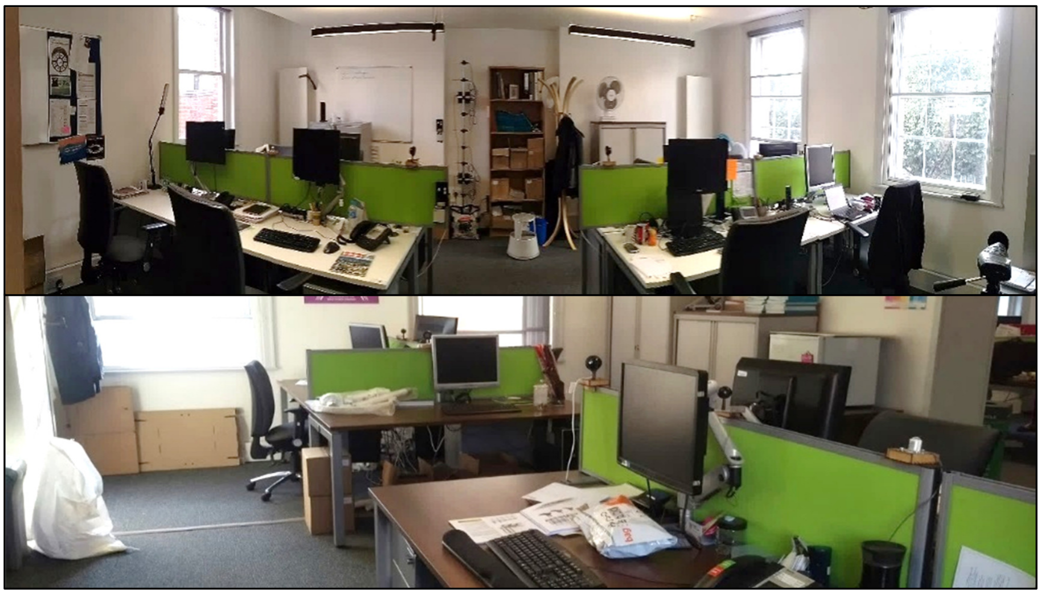

Figure 31. (Above) Internal Layout of Office A. (Below) Internal office layout of Office B (taken with a fisheye lens).

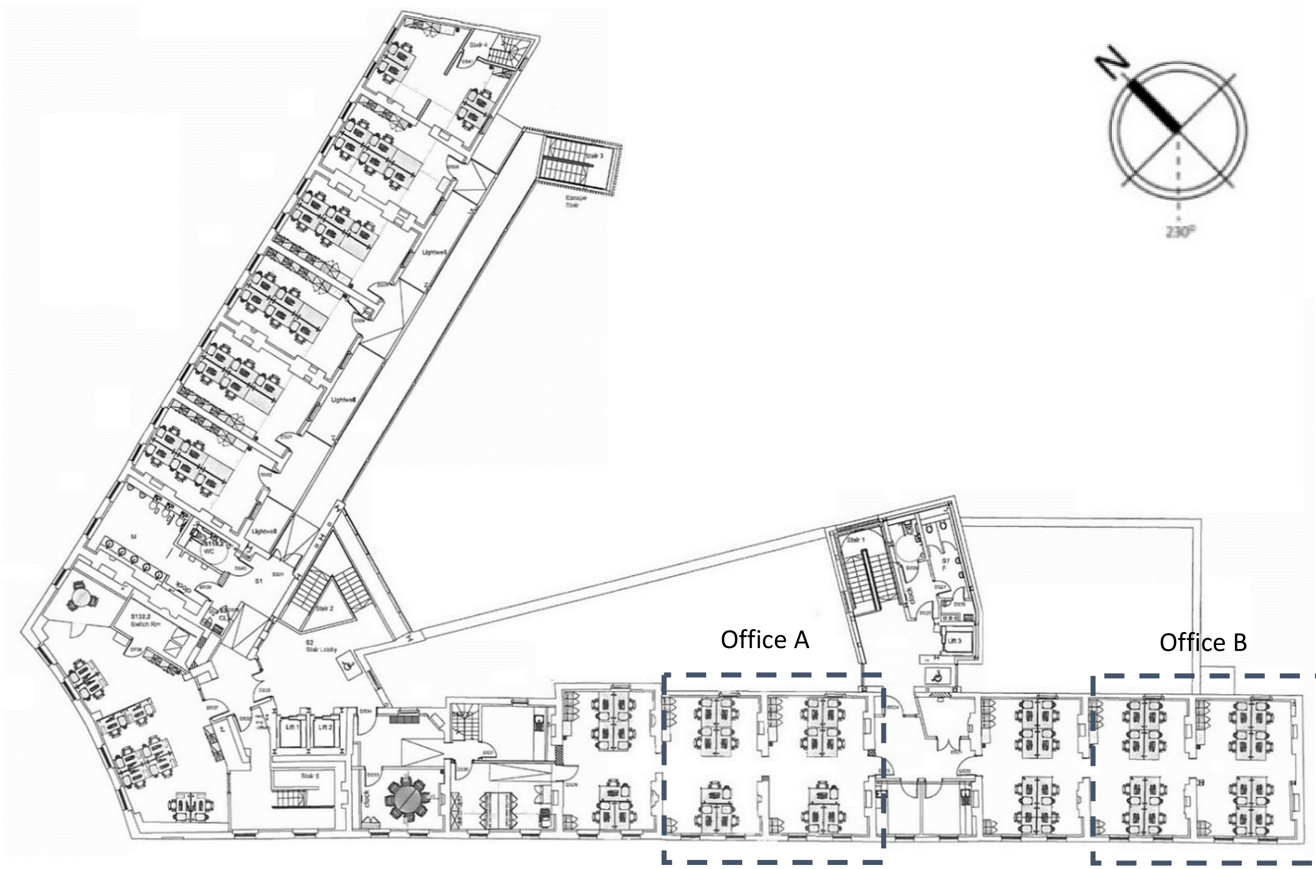

Figure 32. Second Floor Internal Layout of the Clarence Centre

In all offices, electric lighting was provided by four dimmable tube lights (35W/840) which linked to an occupancy sensor. The control of the dimmer was operated by pressing the wall switch located in each segmented office. Two dimmable tube lights were positioned parallel above the north and south desks. Natural ventilation assisted by electric fans was the only method of cooling the office spaces. However, increased noise transmission from the south-west façade prevented the frequent opening and closing of the windows. Central heating was turned off during the summer period and although electric heaters were present in a few of the office spaces, these were not in use during the test period.

At full capacity, the two offices were occupied by 42 members of staff between them, some of whom occupied a desk space for only part of the week. In Office B, hot-desking was a common occurrence as some of the occupant's job roles meant spending large portions of the day in other parts of the university campus. Externally to the building, several obstructions were noted. On the south-west façade, large trees and the surrounding buildings had the potential to block sunlight to the offices in the afternoon. On the north-east façade, the out-set building had the potential to shade the north-east side of the offices in Office A. However, the shading caused by the out-set building was minimal during the time of the test[25] (Figure 30 and Figure 32).

4.3.3 Participant and Company/Site Recruitment

Before recruiting the participants, the study design was approved by the London South Bank University Ethics Committee (see Appendix A). The company/site location and participants were recruited by email. Potential participants were also invited to an optional face to face group session. The email sent to the potential participants included an information pack. This information was also presented through the face-to-face group session. The selection criteria for the participants was based on the following:

- Familiarity with working at a PC as part of their day-to-day job
- Availability during the testing period
- A moderate to fluent competency in English reading and writing
- Willingness to work in the selected open-plan offices
- Willingness to wear a similar type of clothing on each of the test days

The information was collected through a questionnaire included in the consent form. Two options of participation were offered in the information pack:

[25] Between 12 - 2 pm.

- Option 1 involved full participation when completing the questionnaires and tests set. This included agreeing not to interfere with the interventions being placed in the offices.
- Option 2 involved agreement with the Option 1 requirements with the exception that they were not required to take part in the questionnaires or tests.

The participants that decided not to take part in either Option 1 or Option 2 were found alternative workspaces while the interventions were in place. Option 2 was a relatively passive means of participating in the study as the participants did not need to complete any tests or questionnaires. They simply agreed not to interfere with the interventions placed in the offices and stated that they were happy to work in the offices while the interventions were in place. This form of participation was important to obtain to ensure that there was a relatively normal level of occupancy and that all occupants placed in the test conditions understood and agreed to the testing interventions.

In total, 21 participants were recruited for Option 1 of the study and five participants were recruited for Option 2. Two occupants that resided in the testing offices decided that they did not want to take part in the study at all. Alternative work locations were provided for them for the duration of the test period. Even though 21 participants were initially recruited for the full study (Option 1), one participant did not participate in any of the tests or questionnaires. Another participant failed to attend the first test session where the demographic data was collected and so they were removed from the dataset. Nineteen participants’ data was evaluated in the final analysis.

4.3.4 Study Design

The study was conducted in summer 2017 between July and August when both thermal and visual comfort are likely to vary within naturally ventilated buildings due to the external environmental conditions. Qualitative and quantitative data was collected to identify the impact of shading devices on the:

- Objective indoor environment conditions.
- Participant’s subjective perceptions of the environment.
- Subjective perceptions of comfort, health, and well-being.
- Subjective and objective productivity.

Interventions were placed in both offices to create contrasting indoor environmental conditions through the extension and retraction of internal shading products.

4.3.4.1 Data Collection Overview

Within the test phase of the study, the participants were asked to complete a test battery (a combination of tests and questionnaires) at their desk location twice a week over a period of 8 weeks. The test battery included questions about the participants' subjective perception of the indoor environment, as well as their comfort, health and well-being, and perceived level of productivity. This included specific tests designed to evaluate their objective productivity. The test and questionnaire data were collected simultaneously to the quantitative data relating to the objective internal and external environmental conditions. Automatic data collection techniques were used to collect most of the objective environmental data. However, for a few variables, automatic data collection was not viable. Here, manual sensors were used to collect spot measurements. The internal and external environmental data was used to identify the environmental constraints that the test sessions were conducted within.

The objective productivity tests contained work-type and cognitive function tests. The tests were made up of a mixture of paper-based and computer-based tasks supplied by a secure on-line platform. The paper-based tasks were completed in a test booklet that was distributed at the start and collected at the end of each test session.

The participants conducted all test sessions at their dedicated desk location within their office. A focus group and debriefing session was held a week after the final test session. The focus group was conducted in a meeting room separate from the office spaces with the intention of capturing qualitative data that was not possible to capture within the structured questionnaires. The focus group was semi-structured as the participants were asked set questions. However, the participants could explore different topics related to the study. The focus group was recorded, typed up verbatim, and analysed for the themes that related to the effectiveness of the study design.

4.3.4.2 Data Collection Procedure

The test battery was distributed to the participants at 12 noon on Tuesdays and Thursdays over an 8-week period in July and August 2017[26]. The test needed to be completed within a 2-hour period (between 12 noon and 2 pm) and the participants were given flexibility over when they started and finished. In week 9, the focus group and debriefing session was held. The following procedure was followed for each test session:

[26] Except for the first test week where only one test session was conducted within the week (on a Thursday).

- Start of Testing Week 1 – External datalogger activated to log the external data.
- Evening prior to the test session – Interventions placed in the offices.
- 9 am on the test session day – Dataloggers activated to log the internal environmental data.
- Five minutes before the test session – Test booklets distributed to the participants.
- 12 pm – Test battery distributed via a secure online platform link.
- 2 pm – Interventions lifted from the offices.
- 5 - 6 pm – Internal dataloggers stopped and the data offloaded.
- End of Testing Weeks 2, 4, 6, and 8 – External dataloggers stopped and the data offloaded.
- Week 9 – Focus group and de-briefing session held.

4.3.4.3 Study Interventions

On the night prior to all of the test sessions, the following interventions were put in place for the following testing day:

- The shading products were positioned in either the open (retracted) or closed (extended) position.
- The windows were fully closed to reduce the variation between the offices in terms of air velocity, noise, and air quality during testing.
- The occupants were asked not to use electric fans and heaters. Reminder notices were placed on the relevant equipment.
- The electric lighting remained on throughout the test days.

In the first and last test session (1 & 15), the blinds were closed (extended) in both offices and in the remaining test sessions (2 - 14), one office had the blinds open, and the other office had blinds closed. Within each testing week, the participants in each office experienced both blind open and blind closed conditions. Table 18 presents the order that the shading position was tested in in relation to the two offices.

Table 18. Blind Position during the Testing Weeks in each test room.

Date	Test Session	Blind Position	
		Office A	Office B
13.07.17	1*	Closed	Closed
18.07.18	2	Closed	Open
20.07.17	3	Open	Closed
25.07.18	4	Open	Closed
27.07.18	5	Closed	Open
01.08.17	6	Closed	Open
03.08.17	7	Open	Closed
08.08.17	8	Open	Closed
10.08.17	9	Closed	Open
15.08.17	10	Closed	Open
17.08.17	11	Open	Closed
22.08.17	12	Open	Closed
24.08.17	13	Closed	Open
29.08.17	14	Closed	Open
31.08.17	15	Closed	Closed
Total number of sessions with blinds open		6	7
Total number of sessions with blinds closed		9	8

* In Test 1, the participants were presented with a demographic questionnaire and a text typing test only.

4.3.4.3.1 Shading System

New manual screen fabric roller blinds with a τ_e 0.10, ρ_e 0.20, α_e 0.70 values and a τ_v 0.70 were installed on the north-east and south-west façades two weeks before the testing phase. In Chapter 5 of this thesis, the fabric (referred to as Sample A) was tested for its acoustic properties. It was found to have very minimal impact on both the absorption and transmission of sound. These were combined with single glazing on the north-east façade and single and secondary glazing on the south-west façade. The properties of the glazing could not be provided by the university estates management team, therefore the U (U_{tot}) and G -value (g_{tot}) of the window system with and without shading was unidentifiable. The shading system installed on the rooflights was not replaced. This consisted of a Velux system with a block-out blind fabric that was controlled via a manual motorised switch fixed to the north-east façade wall.

4.3.4.4 Test Session Overview

The first test session differed in format to the remaining test sessions. This session was used to collect the participant's demographic data and the baseline text typing performance of all participants when they were under the same intervention condition. This session was also used to trial the distribution of the tests via an emailed link, and to resolve any ICT and login issues related to accessibility to the secured online platform. The following test sessions (2 - 15) presented four isomorphic versions of the full test battery to the participants. The presentation of each test was counterbalanced to reduce the practice effects (Bausell, 2015).

On completion of the test sessions, the test booklets were marked by the researcher and the results were input into a password-protected Excel spreadsheet alongside the data output from the secure online test platform and the environmental data collected from the data loggers and manual sensors. The test battery data was output with a time stamp at the start and end of each test which was aligned with the data collected from the internal environmental sensors. This allowed the objective environmental conditions to be analysed using the participant’s responses to the test battery. Comparisons could be made between the participants in both the blind closed and blind open conditions.

4.3.4.5 Test Battery Design

To be able to evaluate the effect of the internal shading products on the variables listed at the start of Section 4.3.4 (p. 123), the data collected within the test battery needed to consider a wider range of variables. Within the literature, other factors are known to influence the variables being investigated. For example, what an occupant is wearing, and how their gender and age can affect their perception of air temperature (CIBSE, 2015). The data regarding the participant demographics and the objective participant parameters were also collected through the test battery. Questions relating to participant demographic data (e.g., age, gender, job role, and educational achievement) and objective participant parameters (e.g., desk location, length of time at desk, whether they required visual aids, and what they were wearing during the test) were included in the questionnaire in addition to questions about their subjective experience of the internal environment, their perceived productivity level, health, and well-being. Tests were devised to identify their objective productivity level by assessing their cognitive abilities (e.g., working memory, visual acuity, and processing speed) and how they performed when doing common work-based tasks (e.g., text typing, basic arithmetic, and data checking). The variables considered within this study are listed in Table 19.

The variables in Table 19 have been used in previous studies and they have been either identically reproduced or altered to fit the scope of this study. Some of the questions were also altered to prevent misinterpretation / confusion surrounding the meaning of the questions that were identified within the development of the test battery (see Appendix B). The final test battery design was balanced between subjective questionnaires and objective tests for the participants to complete. The questionnaires were split into three sections and the tests were split into a further two sections. The delivery of the questionnaires and the tests were alternated to prevent questionnaire fatigue. The tests were also designed to test the participants' performance on paper and computer-based tasks. Prior to the testing phase, the test battery was trialled in two pilot sessions. The feedback from each pilot session was used to develop and improve the test battery[27]. The test battery and test booklets used were developed by the researcher using Inquisit Lab and various graphic design-based software programs.

Table 19.Test Battery Variables

Variables	Measure
Participant demographic	Age
	Gender
	Job role
	Educational achievement
Objective participant parameters	Desk location and length of time at the desk
	Visual aids
	Clothing level
Subjective comfort	General perception
Subjective productivity	Willingness to exert effort on the tasks
	Belief of the environment impacting productivity
	External variables affecting productivity
Subjective perceptions of the environment	Thermal comfort
	Visual comfort
	Air quality
	Acoustic comfort
Objective productivity	Work type tasks
	Cognitive function tests
Subjective health & well-being	Mood
	Fatigue
	Symptoms of Sick Building Syndrome (SBS)
	Workload questionnaire

The main design constraint for the test battery was that it had to investigate a broad range of variables. It also needed to be short enough to be completed within a reasonable length of time to avoid questionnaire fatigue. Other similar studies that had the objective of identifying the impact of varying indoor environment conditions on productivity using a repeated measures (i.e., a test that is repeatedly given to participants) had test batteries that varied between 5 - 10 minutes and 280 minutes (Heschong Mahone Group, 2003; Lan et al., 2011; MacNaughton et al., 2017; Wargocki, 1999). The final test battery was estimated to take a maximum of 45 minutes to complete with the knowledge that the participants would get quicker once they were familiar with the instructions and the format

[27] Further details of the pilot studies and the design and development of the test battery can be found in Appendix B.

of the tests for each of the tests. This familiarity reduced the testing time to 30 minutes approximately. Even though the selected testing time appeared to be acceptable when making comparisons with similar studies, the duration of the test was reviewed as part of the Focus Group Session (see Section 4.3.4.8, Question 7, p. 160). This meant that the researcher could consider how this may have affected the test data collected.

In the following sections, each of the variables listed in Table 19 and their associated measures are described in more detail with reference to the previous work where similar data has been collected. The presentation of the test battery and accompanying test booklets can be found in Appendix C.

4.3.4.5.1 Participant Demographic Data

Demographic data is often collected in similar studies to ensure that the population being tested is representative of the 'normal' working population (Heschong Mahone Group, 2003; Lan and Lian, 2009; Wargocki et al., 2004). In this study, the data related to the participants' age, gender and highest educational qualification achieved was collected. Each question was presented as a tick box question. The question and options available were given as presented in Figure 33 and Figure 34.

The participants were additionally asked to identify the office that they were working in and their desk location. During the intervention set-up, each office was labelled with an office number and each desk location was given an ID. The participants were instructed where to find this information and to provide this information both on the front of the test booklet and when entering their responses into the online platform.

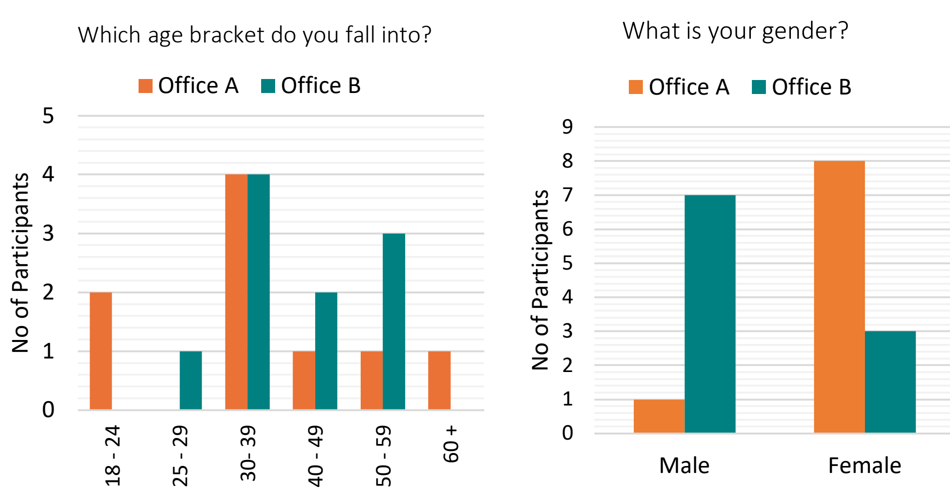

Figure 33. Age (Left) and Gender (Right) of the participants (N=19)

The data reflecting age and gender (Figure 33) shows that Office A was occupied by more female than male participants. Office A had slightly younger participants within the population sample.

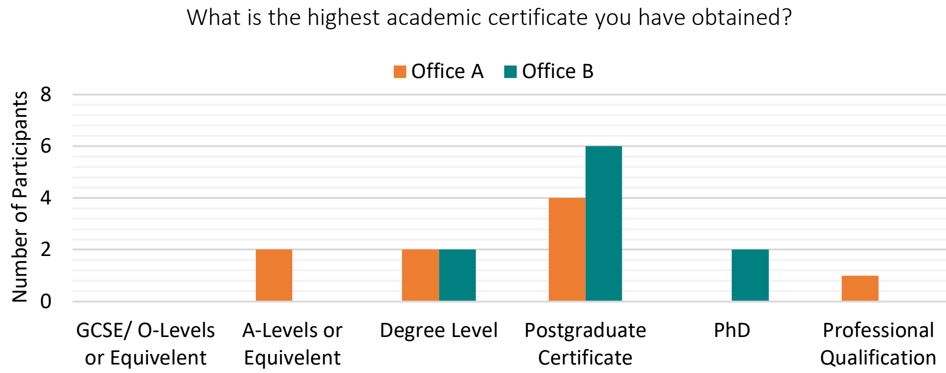

Figure 34. Highest educational qualification achieved by participants (Total N=19)

Figure 34 identifies that there was an almost symmetric distribution within the variation of highest educational achievements obtained by the participants. Most of the participants in both offices had achieved a 'Postgraduate Certificate'.

4.3.4.5.2 Objective Participant Parameters

In test sessions 2 – 15, the participants were asked to identify what they were wearing; whether they were using visionary aids, and the length of time that they spent at their desk location before the test. This data was not used within the analysis because the number of responses were not sufficient to make comparisons between the participants. The study design was unable to account for the variability created by the differences in the participants' clothing level, the visionary aids being used, and the length of time at their desk before the test started.

For each of the test booklets, the participants were asked to fill in their desk and office location as well as their participant ID number. These were recorded and checked by the researcher when collecting the booklets at the end of the test session. Each participants' desk location was added to the testing data output from the online test battery. The desk locations were used to match the participant to their closest internal environmental sensor.

4.3.4.5.3 Subjective Perceptions of the Internal Environment

This section of the questionnaire contained questions relating to the participants' perceptions of temperature, lighting, air quality, and the acoustic environment. They were asked to establish what sensation they felt, whether they felt that their present condition was acceptable, and how they would prefer it to alter (Nicol et al., 2012). Additional questions were added to identify the specific issues surrounding visual comfort (Tanabe and Nishihara, 2004) including identifying glare and the sources of glare, and how the glare experienced made them feel (Geun et al., 2011). However, some of the questions were only presented to the participants if they acknowledged experiencing glare issues.

Most of the questions were presented on bipolar Likert scales of various lengths between 3 and 7-points. Each point on the scale related to a numeric value and an associated answer. For example, when assessing the participants' air temperature sensation, they were asked 'How do you feel the air temperature is at this time in the office?'. The scale ranged from - 3 to + 3 with - 3 representing 'Too Cold', + 3 representing 'Too Hot' and 0 represented 'Neutral'. Following this, - 2 and - 1 related to 'Cool' and 'Slightly Cool' respectively and + 2 and + 1 related to the responses for 'Warm' and 'Slightly Warm'. The presentation of this question was identical to that used within the ASHRAE thermal assessment method (ASHRAE, 2015).

The only question that was not presented on a bipolar Likert scale asked the participants to identify the source of glare in the office. For this question, it was more appropriate to give options for potential glare sources through a tick box question. Six options were offered for participants to choose from which included the computer screen, the window, direct sunlight, electric lighting, a reflection of sunlight, and an unidentifiable source. More than one response could be selected.

For the data analysis, all scales were transposed to either a 1 to 7, 1 to 5, 1 to 4 or 1 to 3 scale. Where appropriate, answers with more positive associations were transposed to give a more positive numeric value. Table 20 and Table 21 show the variable that the question belonged to (e.g., thermal comfort, visual comfort, air quality etc.), what each question was measuring, the question format, the scale extremities, and the question number which relates to the order that the questions were presented in.

Table 20. Subjective perceptions of the environment with the allocated question variable, measure, presented question format, response extremities, and question number (Part 1 of 2).

Variable	Measure	Question Format	Response Extremes		Q No
Thermal Comfort	Air Temperature Sensation	How do you feel the air temperature is at this time in the office?	Cold (-3)	Hot (+3)	1
	Air Temperature Preference	How would you prefer to feel in your office?	Warmer (-1)	Cooler (+1)	2
	Air Temperature Acceptability	How acceptable do you think the air temperature is at this moment?	Clearly Acceptable (-2)	Clearly Unacceptable (+2)	3
Air Quality	Humidity Sensation	How would you describe the level of humidity at this time in the office?	Too Dry (-3)	Very Humid (+3)	4
	Air Freshness Sensation	How would you describe the freshness of the air at this time in the office?	Too Stuffy (-3)	Very Fresh (+3)	5
	Air Odour/Fragrance Sensation	How would you describe the odours/fragrances experienced at this time in the office?	Extremely Pleasant (-3)	Extremely Unpleasant (+3)	6
	Humidity Preference	How would you prefer the humidity of the air to be in the room at this time?	Drier (-1)	More Humid (+1)	7
	Air Freshness Preference	How would you prefer the air freshness to be in the room at this time?	Fresher (-1)	Less Fresh (+1)	8
	Air Odour / Fragrance Preference	How would you prefer the level of odours/fragrances experienced to be in the room at this time?	Less Pleasant (-1)	More Pleasant (+1)	9
Acoustic Comfort	Noise Sensation	How would you describe the level of noise within the room at present?	Very Noisy (-3)	Very Quiet (+3)	16

Table 21. Subjective perceptions of the environment with the allocated question variable, question measure, presented question format, response extremities, and question number (Part 2 of 2).

Variable	Measure	Question Format	Response Extremes		Q No
Visual Comfort	Lighting Sensation	How do you find the level of brightness within the room at present?	Very Dark (-3)	Very Bright (+3)	10
	Visual Strain	Are you experiencing any strain with your eyes whilst completing the questionnaire?	No Strain (0)	Large Amount of Strain (2)	11
	Visual Ease (to read Questionnaire)	Does the lighting at present make it easier or harder to read the questionnaire?	Very Hard (-3)	Very Easy (+3)	12
	Lighting Preference	How would you prefer the lighting to be within the room at present?	Prefer Much Darker (-3)	Prefer Much Lighter (+3)	13
	Lighting Acceptability	How acceptable is the lighting within the room at present?	Clearly Not Acceptable (-2)	Clearly Acceptable (+2)	14
	Identifiable Glare Issues	Are you experiencing any issues with glare from the computer or on your person whilst sitting at your desk?	No (0)	Yes (2)	15
	Glare Source	Can you identify the source of the glare?	N/A	N/A	15 (a)
	Magnitude of Glare	How would you describe the magnitude of the glare?	Does Not Bother Me (0)	Intolerable (4)	15 (b)
	Glare Sensation	How does the glare make you feel?	Very Uncomfortable (0)	Does Not Bother Me (3)	15 (c)
	View Sensation	How satisfied are you with the quality of your view at your current desk location?	Extremely Satisfied (-3)	Extremely Dissatisfied (3)	17

4.3.4.5.4 Subjective Comfort and Productivity

The participants were asked to respond to each question in relation to how they were feeling at that current moment in time under the constraints of the differing interventions. The questions given to the participants in relation to their comfort and productivity are presented in Table 22. The table also identifies the variable that the question relates to, what it measures, the question format, the scale extremities, and the question number which relates to the order that the question was presented in.

The participants were first asked to rate their overall comfort at their desk location. This question was presented as a 7-point Likert scale in a bipolar scale from - 3 to + 3. The presentation of this question was the same as in the work of Nicol et al. (2012). The extremes were transposed to a 1 - 7 polar scale with the extremes mirrored so then a positive response related to a more positive score when analysing the data.

Three methods were used to assess the participants' perception of their productivity. The first related to their belief that they were being affected. This was presented on a 0 - 4 Likert scale. The question itself was based on the question posed by Humphreys and Nicol (2007) but it differed slightly in the wording[28]. A check box question was used to gauge if anything outside of the work environment could be affecting the participants' level of productivity with the options 'Yes', 'No' and 'Maybe' (Sullivan et al., 2013). Lastly, a question previously used by Lan et al. (2011) was used to gauge their willingness to exert effort when completing the tasks set. This was presented on a Visual Analogue Scale (VAS).

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[28] The original question asked, 'Do you feel that at present your productivity is being affected by the quality of your work environment and if so, to what extent?' with responses given on a - 2 to + 2 Likert scale with extremes of 'Much higher than normal' and 'Much Lower than normal' (Humphreys and Nicol, 2007).

Table 22. Subjective perceptions of comfort and productivity with the allocated question variable, question measure, presented question format, response extremities, and question number.

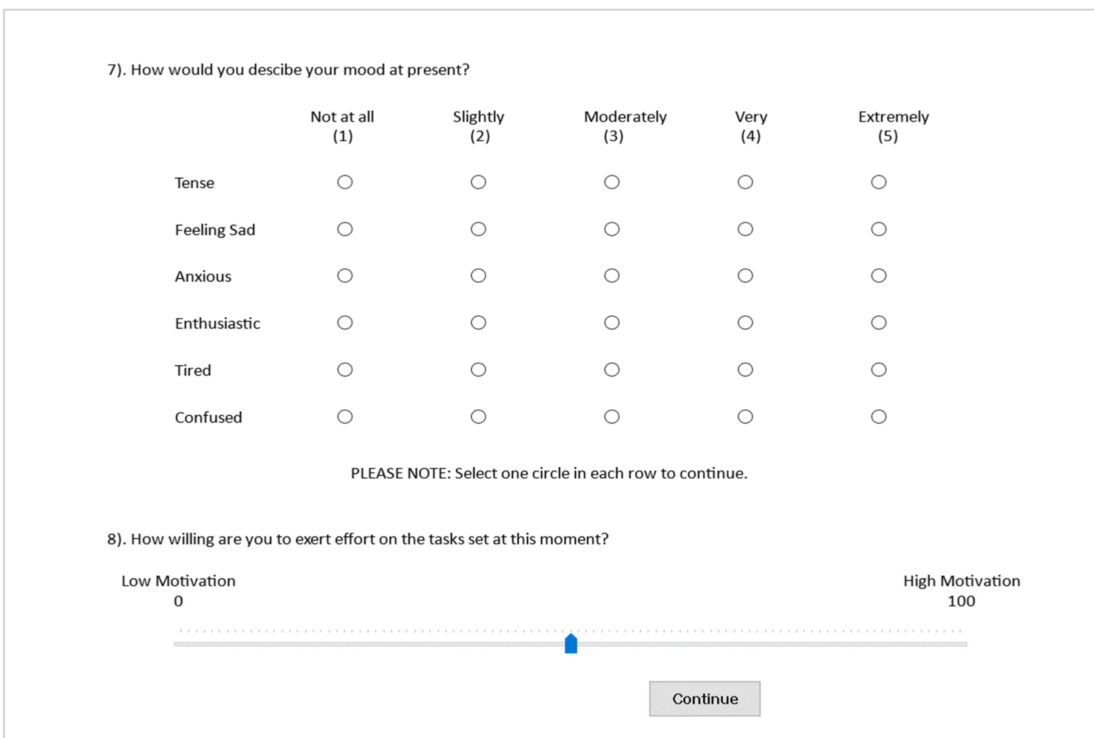
Variable	Measure	Question Format	Response Extremes		Q No.
Subjective Comfort	Overall Comfort Sensation	At this time, how would you rate your overall comfort at your desk location?	Very Comfortable (-3)	Very Uncomfortable (+3)	1
Subjective Productivity	Belief of the environment affecting their work productivity.	For a moment, consider the environment you are working in, taking into account the lighting, temperature, air quality, and level of sound you are experiencing at this time. To what extent do you believe the environment is impacting your work productivity at this moment?	Not at All (0)	Extensively (3)	2
	Presence of external issues that could be affecting their work productivity.	Are there any issues outside of work that may be affecting your productivity level at this moment?	Yes	No	3
	Willingness to exert effort on the tasks set.	How willing are you to exert effort on the tasks set at this moment?	Low Motivation (0)	Highly Motivated (100)	8

4.3.4.5.5 Subjective Health and Well-being

The health and well-being questionnaire was split into two sections, specifically one that was completed before the tests (pre-test) and one that was given after the tests (post-test). In the pre-test questionnaire, the participants were asked to answer questions relating to their mood and a symptom specific fatigue question was given to the participants before conducting the tests. The questions used were based on the questions used by Lan et al. (2011) and Tanabe and Nishihara (2004). Post-test participants were presented with the Sick Building Syndrome (SBS) survey, similar to the one used by Wargocki, (1999), and the mental workload questions used by Lan et al. (2011).

Pre-Test

All questions presented within this section can be found in Table 23. The mood questionnaire was presented to the participants using a gridded tick box system with the overriding question 'How would you describe your mood at present?' with the following answer variables: tense, feeling sad, anxious, enthusiastic, tired, and confused. The question was presented as displayed in Figure 35 with 5 options for the responses listed as a polar scale. The descriptions of the mood states differed slightly to those used by Lan et al. (2011). For example, depression was replaced with feeling sad and vigor was replaced with feeling enthusiastic.


7). How would you descibe your mood at present?

	Not at all (1)	Slightly (2)	Moderately (3)	Very (4)	Extremely (5)
Tense	○	○	○	○	○
Feeling Sad	○	○	○	○	○
Anxious	○	○	○	○	○
Enthusiastic	○	○	○	○	○
Tired	○	○	○	○	○
Confused	○	○	○	○	○

PLEASE NOTE: Select one circle in each row to continue.

8). How willing are you to exert effort on the tasks set at this moment?

Low Motivation 0

High Motivation 100

Continue

Figure 35. Mood Questionnaire and Subjective Productivity Question (Willingness to Exert Effort in the Tasks Set).

The fatigue question was presented as a checkbox question (Figure 36) with seven associated descriptions of fatigue that ranged from ‘Fully Alert, wide awake’ to ‘Completely exhausted, unable to function effectively.’ Each response was output on a 1 - 7 scale with +7 relating to the most positive response (‘Fully Alert’). The seven descriptions of fatigue were chosen from the descriptions of fatigue provided within the work of Tanabe and Nishihara (2004). Each participant was restricted to giving one response.

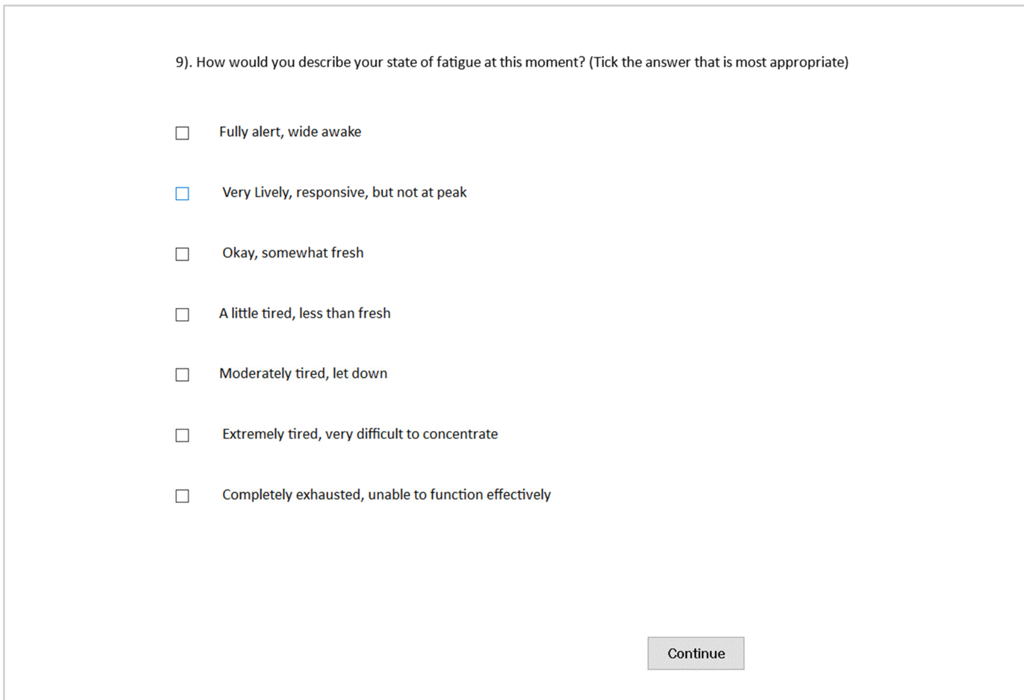


Figure 36. Fatigue Question

Table 23. Health and well-being questionnaire (pre-test) with the allocated question variable, question measure, presented question format, response extremities, and question number.

Variable	Measure	Question Format	Response Extremes		Q No.
Health and Well-being	Mood: Feeling…	How would you describe your mood at present?			
	…Tense	Tense	Not at All (1)	Extremely (5)	7(a)
	…Sad	Feeling Sad			7(b)
	… Anxious	Anxiety			7(c)
	… Enthusiastic	Enthusiastic			7(d)
	…Tired	Tired			7 (e)
	…Confused	Confused			7(f)
	Description of Fatigue	How would you describe your state of fatigue at this moment?	Fully Alert	Completely Exhausted	9

Post-Test

A Sick Building Syndrome (SBS) survey was presented to the participants on a VAS where the participants provided a response by moving a slider along the 0 - 100 scale. The extremes of the scale are associated with a given response. Table 24 presents the extremes for each of the VAS questions.

The workload questionnaire used by Lan et al. (2011) was incorporated. This asked the participants to assess the mental, physical, and temporal demand of the tasks set within the test battery. It also asked the participants what their perception was of their overall performance and how much effort they had to put in to obtaining their level of performance. These questions were delivered at the very end of the test battery after all of the tests had been completed and were presented on five VAS scales. Five further questions were given which assessed the participants' mood after the tests. Within the work of Lan et al. (2011), the participants' frustration level with a given task was assessed by asking the participants 'How insecure, discouraged, irritated, stressed, and annoyed were you?'. In this study, this question was split into five questions relating to one of the mood states in the question and related to the specific tests that they had carried out. The exact wording of the questions created can be found in Table 25. Like Lan et al. (2011), the five questions were also presented using a 0 - 100 VAS scale.

To interpret the SBS survey and the workload question data, the responses were translated from the 0 - 100 scale into categorical data. The scores were grouped into five groups: 0 to 20, 21 to 40, 41 to 59, 60 to 79, and 80 to 100. These five groups were then given balanced associations by the researcher which differed depending on the question and the extremes presented to the participants. For the SBS survey, the extremes, 0 - 20 and 80 - 100, were represented by a symptom (e.g., Nose Clear and Nose Blocked). A neutral association was given to scores between 41 and 59. 'Slightly' was given to the scores between 21 - 40 and 60 - 79 (e.g., 'Slightly Clear' and 'Slightly Blocked'). For questions 7 – 9 in the workload questionnaire, 'Very' related to scores between 0 and 20 and 80 to 100 while a neutral association was given to the scores between 41 – 59. 'Slightly' was given to scores that fell between 21 - 40 and 60 - 79. For questions 11 – 16, the categories were labelled 'Not at all' (0 - 20), 'A little' (21 - 40), 'Somewhat' (41 - 59), 'Moderately' (60 - 79), and 'Very' (80 - 100). Question 10 was similar apart from the first category was labelled 'Unsuccessful'.

Table 24. Health and well-being questionnaire (post-test) with the allocated question variable, question measure, presented question format, response extremities, and question number (Part 1 of 2).

Variable	Measure	Question Format	Response Extremes		Q No.
Health and Well-being (SBS Symptoms)	Nose: Clear or Blocked?	On a scale from 0 to 100, how do you feel at the present time?	Nose Clear	Nose Blocked	1 (a)
	Nose: Dry or Running?		Nose Dry	Nose Running	1 (b)
	Mouth: Dry or Running?		Mouth Dry	Mouth Running	1 (c)
	Lips: Dry or Not Dry?		Lips Dry	Lips Not Dry	1 (d)
	Skin: Dry or Moist?		Skin Dry	Skin Moist	2 (a)
	Hair: Dry/Brittle or Not Dry/Brittle?		Hair Dry/Brittle	Hair Not Dry / Brittle	2 (b)
	Nails: Brittle or Supple?		Nails Brittle	Nails Supple	2 (c)
	Eyes: Dry or Not Dry?		Eyes Dry	Eyes Not Dry	2 (d)
	Eyes: Smarting/Hurting or Not Smarting/ Hurting?		Eyes Smarting / Hurting	Eyes Not Smarting/Hurting	3 (a)
	Eyes: Aching or Not Aching?		Eyes Aching	Eyes Not Aching	3 (b)
	Eyes: Feel Gritty or Not Gritty?		Eyes Feel Gritty	Eyes Not Gritty	3 (c)
	Headache Symptoms		Severe Headache	No Headache	3 (d)
	Clarity of Thinking		Head Clear	Difficult to Think	4 (a)
	Dizziness Sensation		Not Dizzy	Dizzy	4 (b)
	General Feeling		Feeling Bad	Feeling Good	4 (c)
	Tiredness (Post-test)		Tired	Rested	4 (d)
	Ability to Concentrate		Difficult to Concentrate	Easy to Concentrate	5 (a)
	General Attitude		Depressed	Positive	5 (b)
	Alertness		Alert	Sleepy	5 (c)
	Office Cleanliness	On a scale from 0 to 100, how would you describe your office environment at the present time?	Office Dusty/Dirty	Office Clean	6 (a)

Table 25. Health and well-being questionnaire (post-test) with the allocated question variable, question measure, presented question format, response extremities, and question number (Part 2 of 2).

Variable	Measure	Question Format	Response Extremes		Q No.
Health and Well-being	Mental Demand Required	On a scale from 0 to 100, how mentally demanding were the tasks set?	Very Low (0)	Very High (100)	7
	Physical Demand Required	On a scale of 1 to 100, how physically demanding were the tasks set?	Very Low (0)	Very High (100)	8
	Pace of the Tasks	On a scale of 1 to 100, how did you find the pace of the tasks set?	Very Slow (0)	Very Hurried (100)	9
	Successfulness in completing the Tasks	On a scale of 1 to 100, how successful do you believe you were in accomplishing what you were asked to do within the tasks set?	Unsuccessful (0)	Very Successful (100)	10
	Amount of effort required to achieve the level of performance on the Tasks Set	On a scale of 1 to 100, how hard did you have to work to achieve your level of performance on the tasks set overall?	Not at all Hard (0)	Very Hard (100)	11
	Feeling Insecure when completing the Tasks Set	On a scale of 1 to 100, how insecure did you feel whilst completing the tasks set?	Not at All Insecure (0)	Very Insecure (100)	12
	Feeling Discouraged when completing the Tasks Set	On a scale of 1 to 100, how discouraged were you whilst completing the tasks set?	Not at All Discouraged (0)	Very Discouraged (100)	13
	Feeling Irritated when completing the Tasks Set	On a scale of 1 to 100, how irritated were you whilst completing the tasks set?	Not at all Irritated (0)	Very Irritated (100)	14
	Feeling Stressed when completing the Tasks Set	On a scale of 1 to 100, how stressed were you whilst completing the tasks set?	Not at all Stressed (0)	Very Stressed (100)	15
	Feeling Annoyed when completing the Tasks Set	On a scale of 1 to 100, how annoyed were you whilst completing the tasks set?	Not at all Annoyed (0)	Very Annoyed (100)	16

4.3.4.5.6 Objective Productivity

The objective productivity measures included two types of productivity variables: work type tests and cognitive function tests. The tests were chosen on the basis that:

- They had been used in previous studies and significant results were found when the thermal and visual conditions altered, or
- They tested cognitive abilities that are linked to common work-related tasks.

The studies that the tests have been used in previously are referenced in the following sections. The tests were delivered in two sections between the questionnaires. Before each test, an instruction page was presented on-screen which contained a mixture of text, image and animated (gif) instructions. The participants were asked to hit enter on the keyboard once they had read the instructions in full.

Table 26 and Table 27 identify the test type (work-based or cognitive function), the name of the test, what the assessment criteria were for each test, what skill or function was tested through the test (referred to as the 'Test Attribute'), and the test number which represents the order that the tests were presented in. The functionality and presentation of the tests are further described in this section.

Table 26. Objective productivity (work type) tests and their assessment criteria, test attributes, and test number (Part 1 of 2)

Variable	Measure / Test	Assessment Criteria	Test Attribute	Test No.
Work Type Tests	Text Typing	Number of words typed per minute (WPM)	Text Typing Speed	1
		Number of errors made	Typing Errors	
		Accuracy of words typed (%)	Typing Accuracy	
	Arithmetic	Mean difference in time between the addition and subtraction task and the alternating task (s)	Task Switching Speed	2
		Mean difference in accuracy between the addition and subtraction task and the alternating task (%)	Task Switching Accuracy	
	Data Checking	Number of questions answered within a set time limit	Data Entry Speed	3
		Number of questions answered correctly	Data Entry Correct	
		Accuracy of questions answered (%)	Overall Data Entry Accuracy	
	Grammar	Total number of correct answers	Grammatical Reasoning	6

Table 27. Objective productivity (cognitive function) tests and their assessment criteria, test attributes, and test number (Part 2 of 2)

Variable	Measure / Test	Assessment Criteria	Test Attribute	Test No.
Cognitive Function Tests	Number Search	Time taken to respond (s)	Visual Acuity Speed	4
		Accuracy of responses (%)	Visual Acuity	
	Reaction Time	Mean time taken to answer correctly (s)	Reaction Speed (for correct answers)	5
		Mean time taken to answer incorrectly (s)	Reaction Speed (for incorrect answers)	
		Mean time to provide all responses (s)	Overall Reaction Speed	
	Processing Speed and Accuracy (Stroop)	Mean time to respond to control stimuli (s)	Processing Speed	7
		Mean time to respond to incongruent stimuli (s)		
		Mean time to respond to congruent stimuli (s)		
		Accuracy of responses to control stimuli (%)	Processing Accuracy	
		Accuracy of responses to incongruent stimuli (%)		
		Accuracy of responses to congruent stimuli (%)		
	Short-Term Memory	Number of correct answers	Short-Term Memory	8
	Working Memory	Number of digits recalled correctly	Memory Recall	9
	Long-Term Memory	Number of correct answers	Long-Term Visual Memory	10

4.3.4.5.6.1 Work Type Tests

4.3.4.5.6.1.1 Text Typing

The text for the text typing test was given to the participants as part of the printed booklet. The participants were asked to type the text on the computer into the text box (Figure 37) as accurately but as quickly as possible.

Figure 37. On-screen presentation of the Text Typing Test

A countdown timer was shown on screen that counted down for 60 seconds and then ended the task once the timer got to zero. The participants were reassured in the instructions that they were not expected to complete the task in full.

The text typing test was marked based on the number of words typed per minute (WPM) and the number of errors made. Their text typing accuracy score was calculated from this.

4.3.4.5.6.1.2 Arithmetic (Plus and Minus)

The arithmetic test (also known as Plus and Minus Test) was given as a paper-based task combined with responses entered on-screen. Three printed pages of two-digit numbers were given to the participants. For the first page (addition), the participants were asked to add 3 to each two-digit number. On the second page (subtraction), they were asked to subtract three, and on the final page (switch task) they were asked to alternate between adding and subtracting 3 from each number. At the end of each page, the participants were asked to click a button on-screen to indicate when they had finished each page of questions (Figure 38). The mean time (s) and accuracy score (%) were both calculated based on their performance in the addition and subtraction only pages of the test and the switching task was deducted from this to give the time and accuracy cost of task switching.

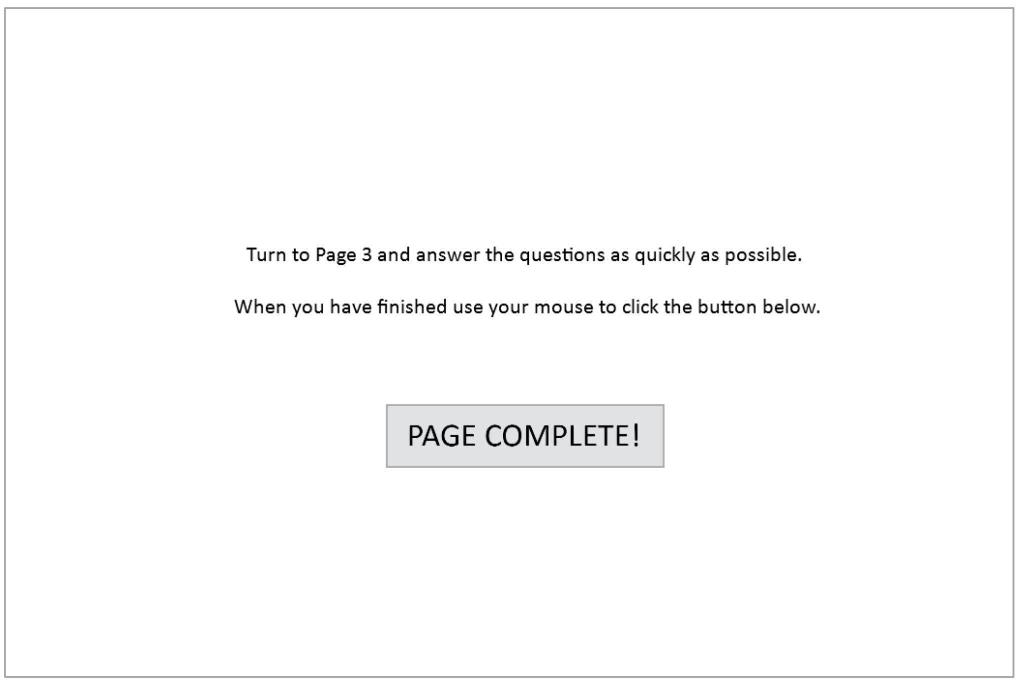


Figure 38. On-screen presentation of the Plus and Minus Test

4.3.4.5.6.1.3 Data Checking

The data checking test asked the participants to read and compare the printed material within two tables. It asked them to check and identify the types of errors in each row. The answers were then input on-screen as a tick box exercise. The participants were given 3.5 minutes to complete as many rows of the table as possible (Figure 39). The test was marked based on the number of questions answered within the timeframe, the number of those questions that were answered correctly, and the percentage of correct answers.

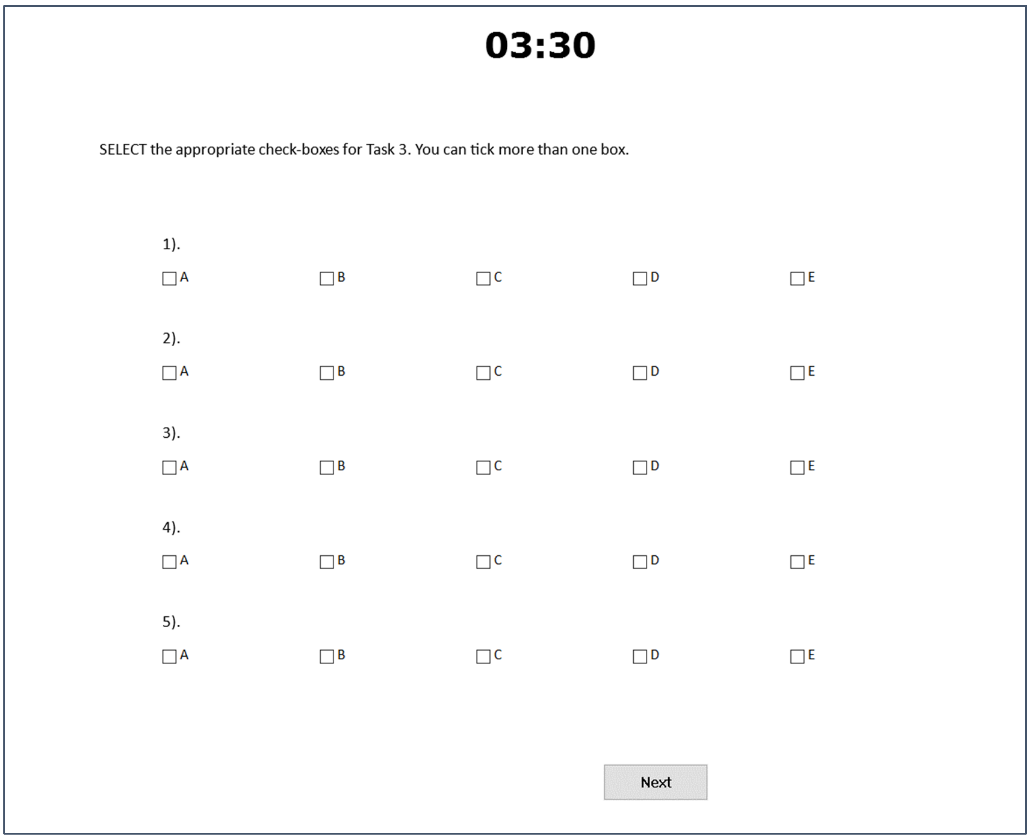


Figure 39. On-screen presentation of the Data Entry Test

4.3.4.5.6.1.4 Grammar

Fifteen sentences were given to each participant presented on-screen. The first eleven assessed their grammatical reasoning by asking the participants to select the missing word from three given options. The last four questions asked the participants to identify either the grammatical meaning within a sentence or the sentence using the correct grammar from a choice of four options. The test was marked based on the number of questions answered correctly and each question was presented as shown in Figure 40.

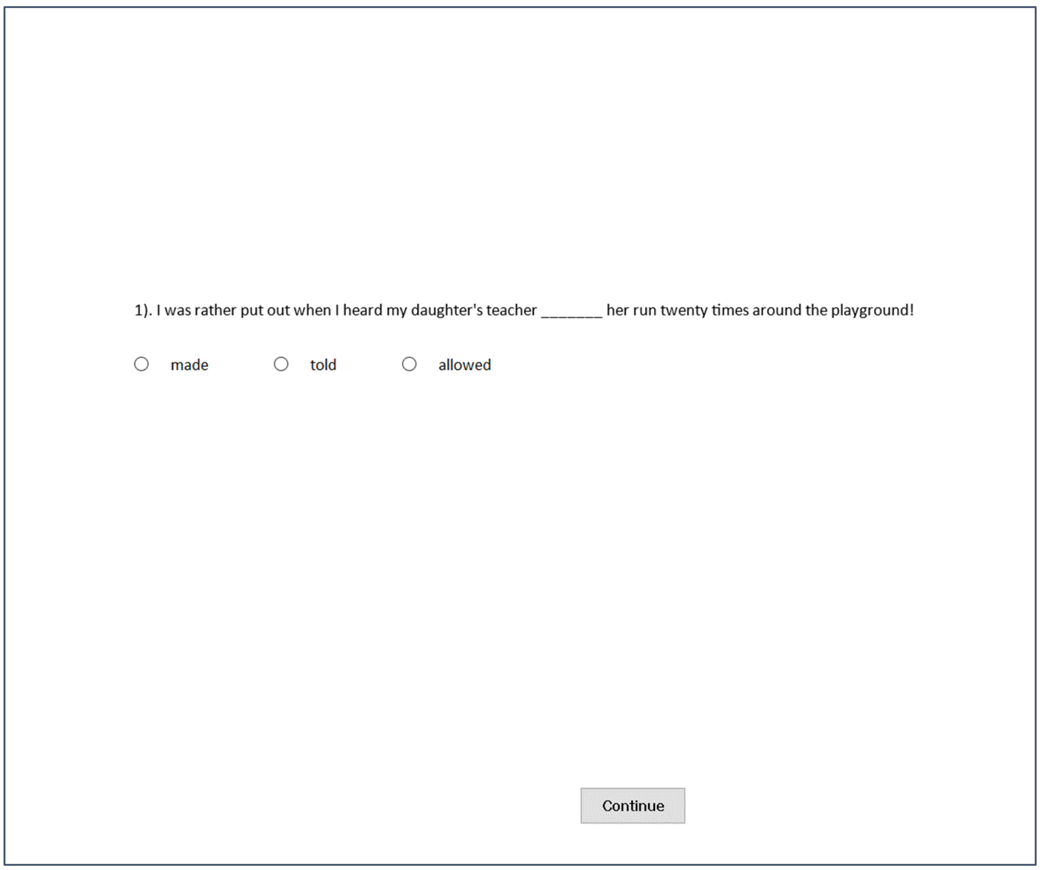


Figure 40. On-screen presentation of Grammar Test

4.3.4.5.6.2 Cognitive Function Tests

4.3.4.5.6.2.1 Number Search / Visual Acuity

Each participant was presented with an 8 x 8 matrix consisting of single digit numbers and they were asked to count how many times a specific digit appeared within the matrix (Figure 41). They were asked to answer the question as quickly as possible by typing the answer in the text box and then clicking the finish button once completed. This test was marked based on the accuracy of their answer and the time taken to respond to the question.

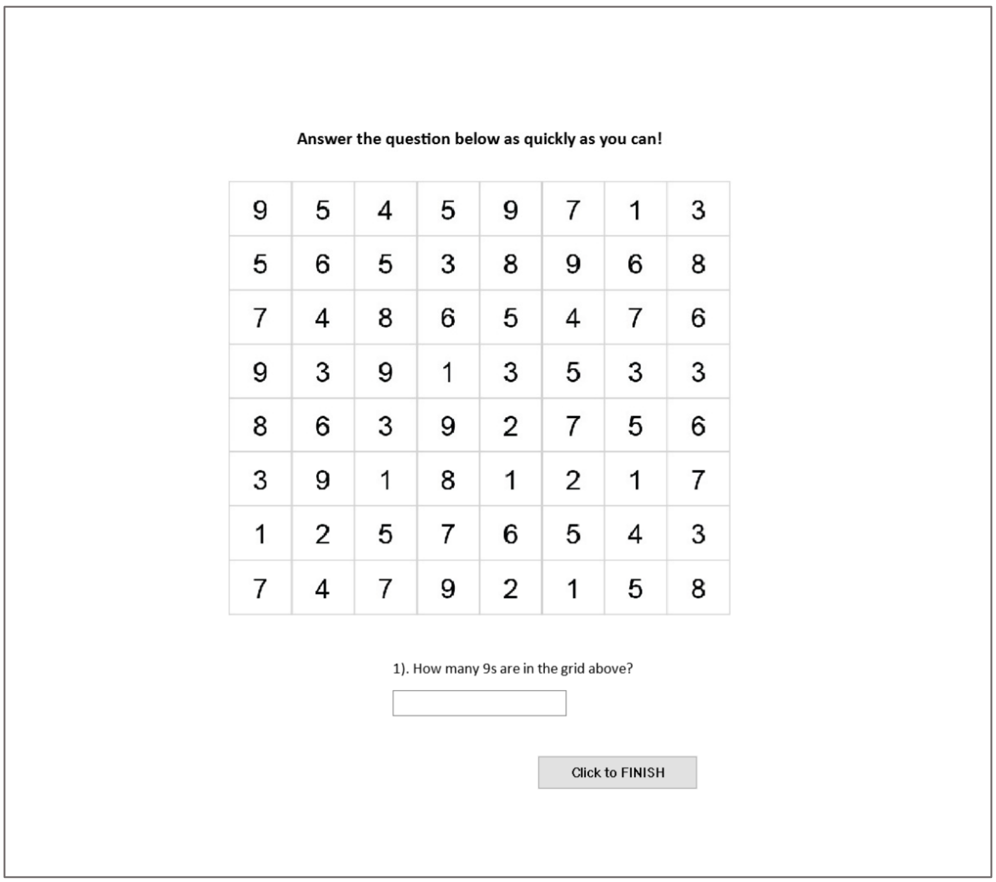


Figure 41. On-screen presentation of the Number Search Test

4.3.4.5.6.2.2 Reaction Time

The participants were informed that four black boxes would appear on the screen and that when one of the four boxes turned red, they were required to press a corresponding key on their keyboard as quickly as possible. An example is shown in Figure 42. This test was scored based on the mean reaction time of each trial. The scores for this task were assessed based on the number of correct and incorrect responses, and their mean response time for correct and incorrect trials.

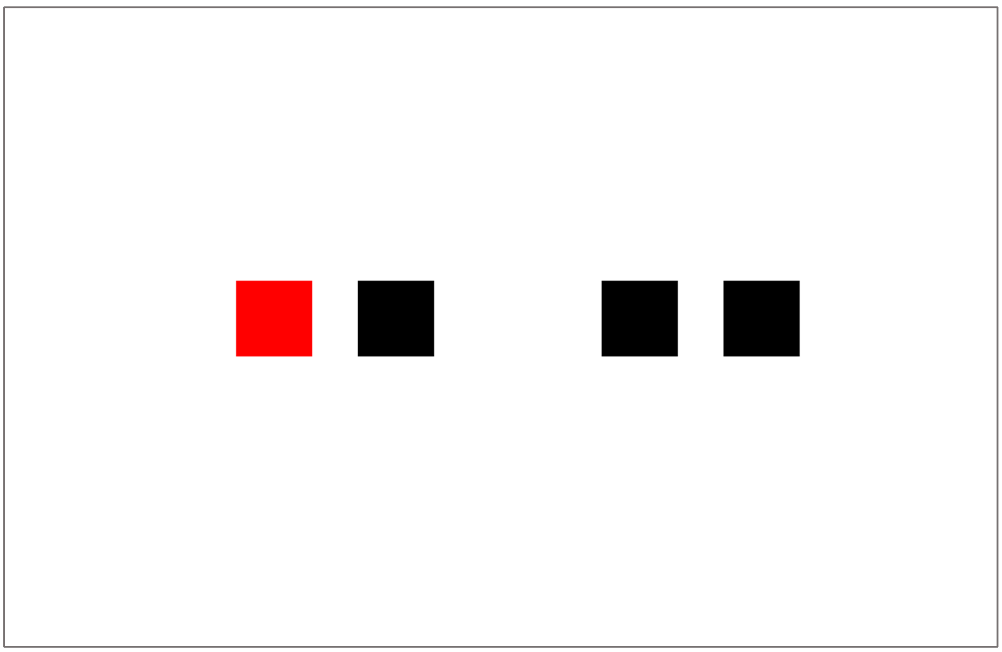


Figure 42. On-Screen presentation of the Choice Reaction Test

4.3.4.5.6.2.3 Processing Speed and Accuracy (Stroop)

A series of stimuli were presented to the participant and on the presentation of each stimulus, the participant was asked to respond with the colour of the text or shape by pressing a corresponding key on their keyboard. The test measured semantic interference when an incongruent stimulus was presented. For example, when the word “blue” is presented in the colour red as found in Figure 43. Control and congruent pairs of stimuli were also given (e.g., a red square as a control pair and the word “red” in red as a congruent pair). The response time and accuracy of the response to each type of stimuli were measured to provide a measure of the participant’s processing speed and accuracy.

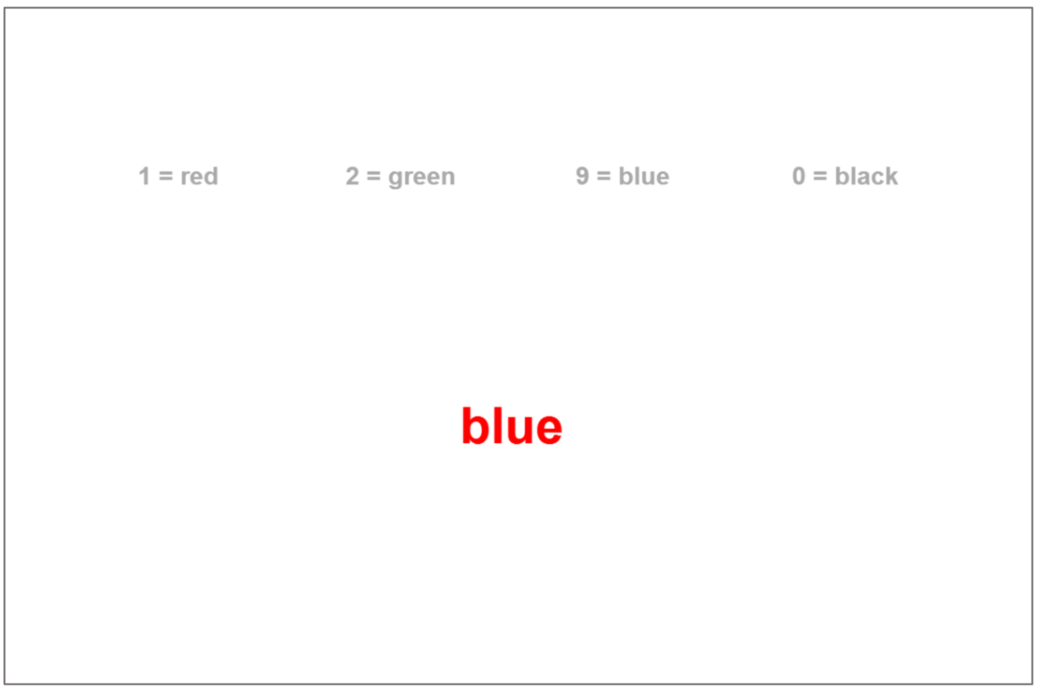


Figure 43. On-screen presentation of the Processing Speed and Accuracy Test (Incongruent Stimuli)

4.3.4.5.6.2.4 Short-Term Memory

Directly after the grammar test, an unprompted question regarding the content of the fifteen grammar test questions was given. A text box was given for the participants to type their answer into as shown in Figure 44. These were marked based on whether their response was correct or incorrect.

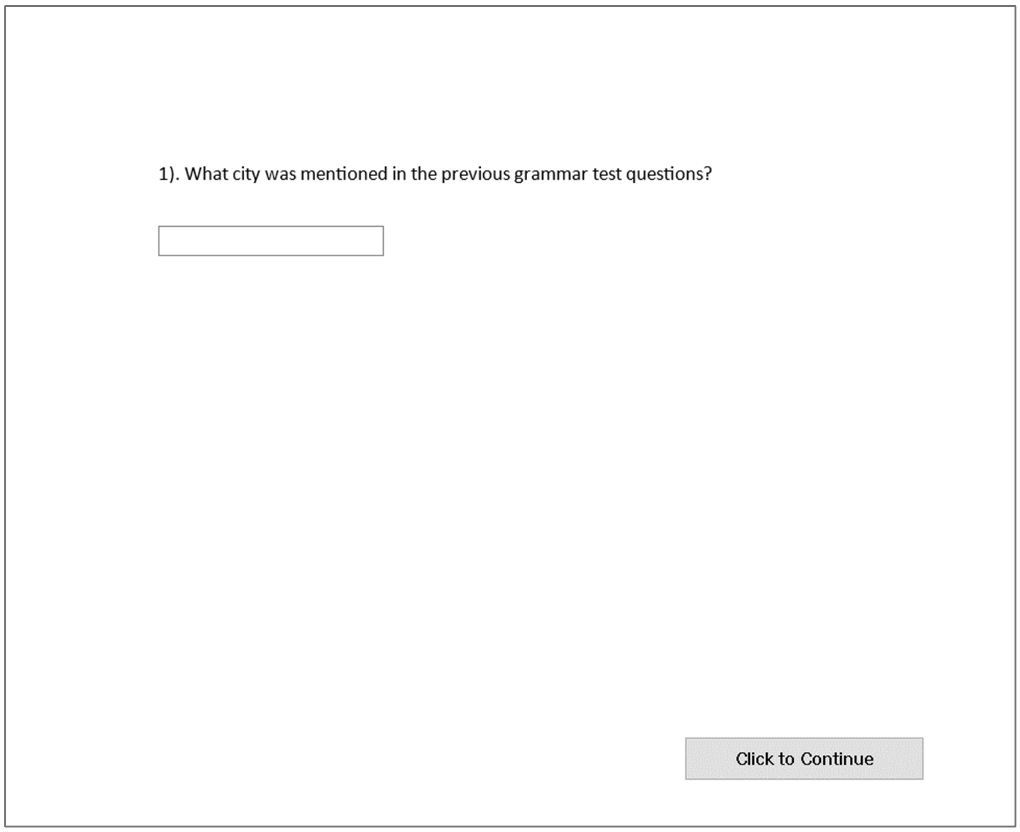


Figure 44. On-screen presentation of the Short-Term Memory Test

4.3.4.5.6.2.5 Working Memory

The working memory of the participants was tested via a backward digit span test. The participants were asked to memorise a series of digits that were presented on-screen, and they were then asked to recall the sequence in reverse order. To signal the start and end of the sequence, a red circle was shown. The participants were asked to type their answers into a blank text box after the sequence had been shown (Figure 45).

The first trial of the test presented four sequences of 3-digit numbers to the participant. If the participant recalled the numbers in reverse order correctly three times, they moved onto the next trial which increased the number of digits to recall by 1 up to 8 digits. If the participant failed to get three out of the four sequences correct at any point in the trial, the test ended, and the participant was presented with the highest number of digits recalled correctly. The test was scored based on the highest number of digits recalled correctly.

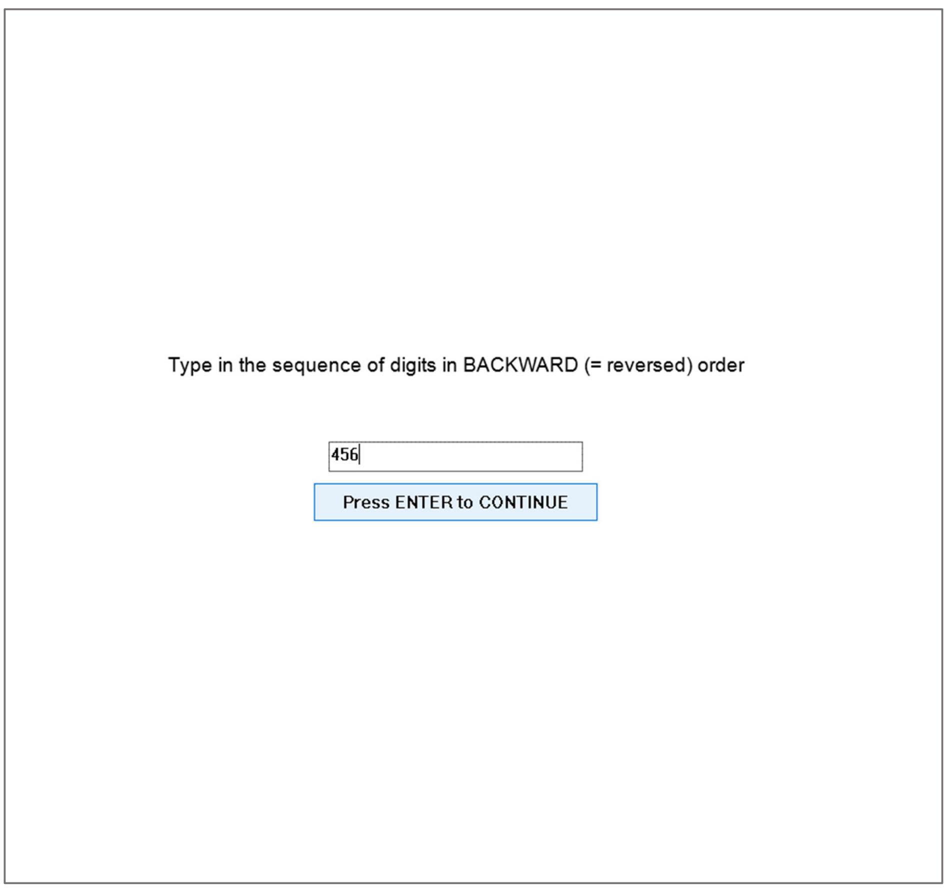


Figure 45. On-screen presentation of the Working Memory Test (Answer Page).

4.3.4.5.6.2.6 Long-Term Memory

A grid of black and white vector images of recognisable objects/symbols (Figure 46) was presented on screen for 60 seconds in test session 2. The participants were asked to remember each item within the grid. After approximately 10 minutes of further tests and questions, the participants were asked to remember what objects/symbols they had seen in the image at the start of the test. They were given two minutes to type out as many answers as they could into a blank textbox as shown in Figure 47. In each subsequent test session (3 -15), they were not presented with the images, but they were asked to remember what objects/symbols were shown to them in the second test session. The test was scored based on the number of images that they recalled correctly in each test session. The text typed was marked by the researcher, and any synonyms and spelling errors were allowed for when marking the participants' responses. For example, if one participant identified a symbol as an 'aeroplane' and another as a 'jet plane', they were both awarded a point.

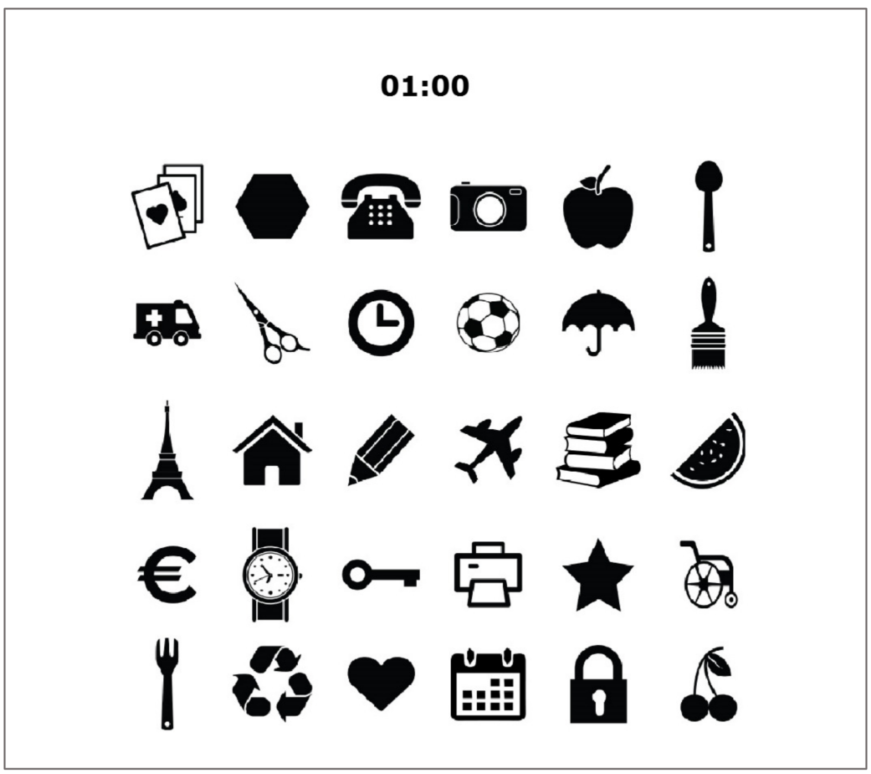


Figure 46. On-screen presentation of objects/symbols for the Long-Term Memory Test

Figure 47. On-screen presentation of the answer page of the Long-Term Memory Test.

4.3.4.6 Internal Objective Environmental Measures

4.3.4.6.1 Automated Data Collection

To prevent interference with the office occupants, the installation of all monitoring equipment took place out of office hours and two weeks prior to the first test session to allow the participants to become familiar with the additional equipment within the office. Each set of internal measurement sensors was connected to a datalogger which offloaded the data to a connected laptop. This data was time stamped and offloaded by the researcher at the end of each testing day.

The acoustic sensors logged the data independently and were calibrated externally. All other sensors were connected to a datalogger and were calibrated by the researcher. This was carried out before testing for all of the sensors except for the operative temperature sensors. This was conducted post testing due to the time constraints. This process is further described in Appendix D.

The layout of the sensors used for remote monitoring can be found in Figure 48. A full list of the equipment installed, and the accuracy tolerances are presented in Table 28.

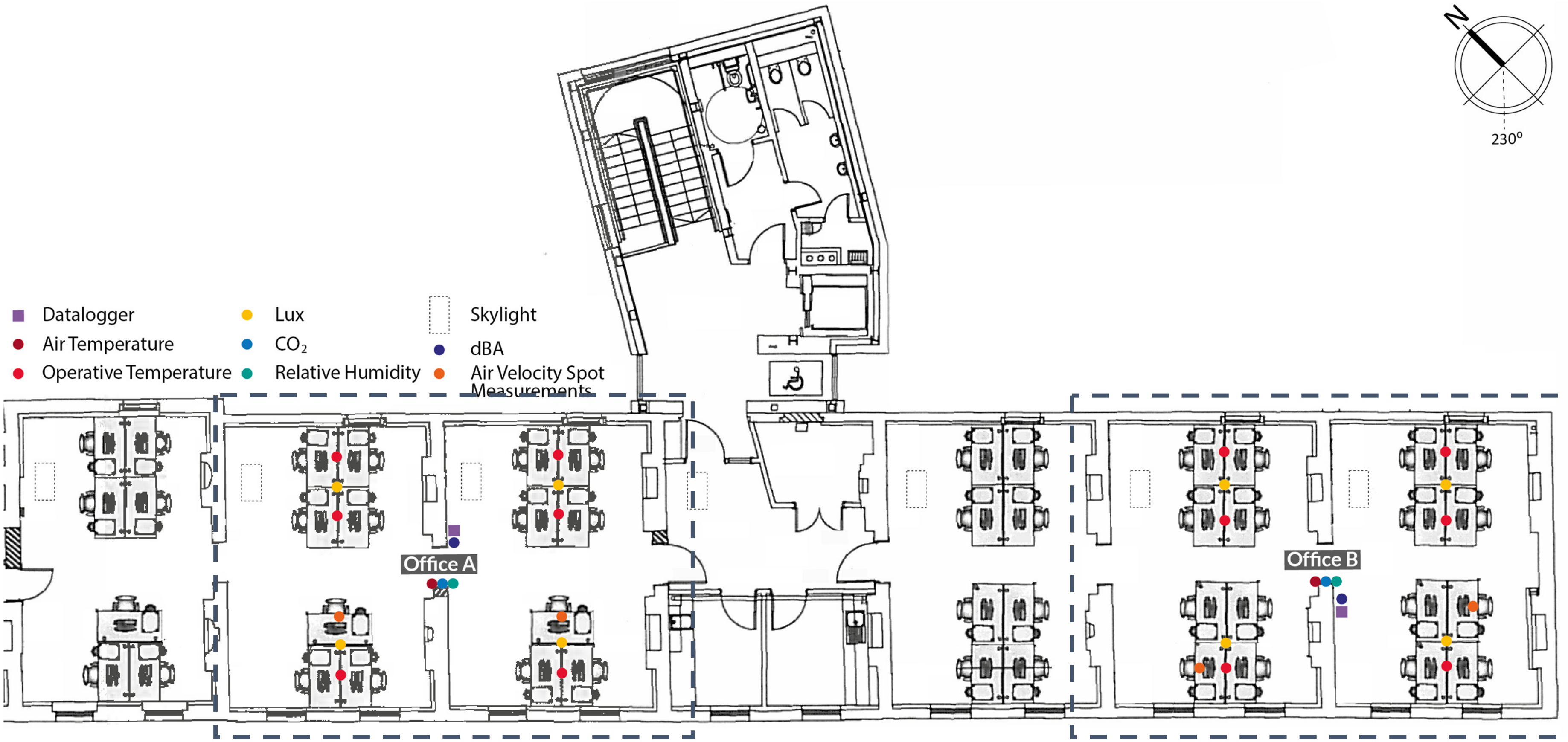


Figure 48. Sensor Schematic

Table 28. Equipment specifications of the logged data

Office A	Office B	Measure	Equipment	Frequency (s)	Quantity (per office)	Scale	Accuracy	Position above Floor Plate
dataTaker DT500	dataTaker DT80	Lux Level (Horizontal)	EKO-ML-020S-O	10	4	0 - 150 Klux	2.3% (Photopic CIE Scale)	1.2m (Horizontal Plane)
		Globe Temperature	36 ø black globe with T - Type, PTFE flat 2-Core Thermocouples	10	6	-25°C - 250°C	± 0.5°C	1.2m
		Air Temperature	GS-CO2-RHT-1001 Sontay	10	1	0 - 40°C	± 0.5°C	1.5m
		Relative Humidity	GS-CO2-RHT-1001 Sontay	10	1	0 - 100%	±3% RH (20 to 80%)	1.5m
		Carbon Dioxide	GS-CO2-RHT-1001 Sontay (Office A)	10	1	0 - 2000 ppm	±50 ppm ±3% of scale	1.5m
			SenseAir K33 (Office B)	60 (Sampling 30s)	1	0 - 2000 ppm	±15 ppm	1.5m
		Acoustics	Testo 816-1	60	1	dBA		1.2m

*Sense Air K33 Data was provided by the Managing Air for Green Inner Cities (MAGIC) project and calibrated by the MAGIC team.

4.3.4.6.2 Spot Measurements

Air velocity was measured using an un-silvered Kata Thermometer[29] with a Kata Factor of 525 (36.5°C) during two sessions at three desk locations. Three measurements were taken during the penultimate test session and one measurement was taken on the last test session. The measurements were taken at the desk locations identified within Figure 48. Where possible, the measurements were taken at desk locations where the air velocities were likely to be higher as they were close to walkways, in offices where the windows were open, or close to closed windows. The measurements were repeated three times at each of the desk locations to give an average cooling time. Equation 7 was then used to calculate the air velocity using the average cooling time and the average air temperature when the measurements were taken (Ellis et al., 1972; London South Bank University, no date; Mcconnell and Yagloglou, 1924; Zeman et al., 2010). The data was collected from the datalogger within each of the offices.

$$\nu = \left(\frac{\frac{\mathrm{H}}{\varepsilon} - \mathrm{a}}{\mathrm{b}}\right)^2 \qquad \text{(Equation 7)}$$

ν = Air Velocity in m/s

H = Cooling Factor = Kata Factor (525) / Cooling Time

ε = Difference between mean Kata temperature and Air Temperature (Dry Bulb)

a = constant of 0.1 (and relevant to the Kata Thermometer used)

b = constant of 0.37 (and relevant to the Kata Thermometer used)

All air velocities calculated were measured below 0.1 m/s, signifying that the air flow within the offices was still. This allowed the researcher to assume that the air velocities within the two offices were equal and would not have affected the participants' thermal comfort conditions. It also allowed the researcher to assume that the globe temperature recorded was representative of the operative temperature (ϴ) within the room (CIBSE, 2015). The

[29] A kata thermometer is a heated-alcohol thermometer. When heated to 100°C, the time it takes to cool can be measured and used to determine the air velocity. The kata bulb is placed in boiling water (100°C) until the liquid within the thermometer partly fills the reservoir at the top of the thermometer. The thermometer is then removed from the heat source, dabbed dry and timed for the time it takes for the liquid to drop between two temperature marks on the thermometer. This gives a cooling time. The benefit of using a kata thermometer over other methods of measuring air velocity is that it is relatively inexpensive and can measure very low (< 0.1 m/s) air velocities. However, the measurement procedure and the results are not instantaneous.

globe temperature will now be referred to as the operative temperature throughout the remainder of this study.

4.3.4.7 External Objective Environment Measures

The external weather station was set up on top of the Centre for Efficient and Renewable Energy in Buildings at London South Bank University as seen in Figure 49. The exact location in relation to the Clarence Centre can be found in Figure 50. The weather station was set up with an air temperature sensor (SKTS 200/U/I), south-west facing vertical pyranometer (CMP3), and a horizontal lux sensor (SKL 310). All sensors were linked to a datalogger which logged an average value reading every 10 minutes for the values taken every 60 seconds. All external monitoring equipment was externally calibrated.

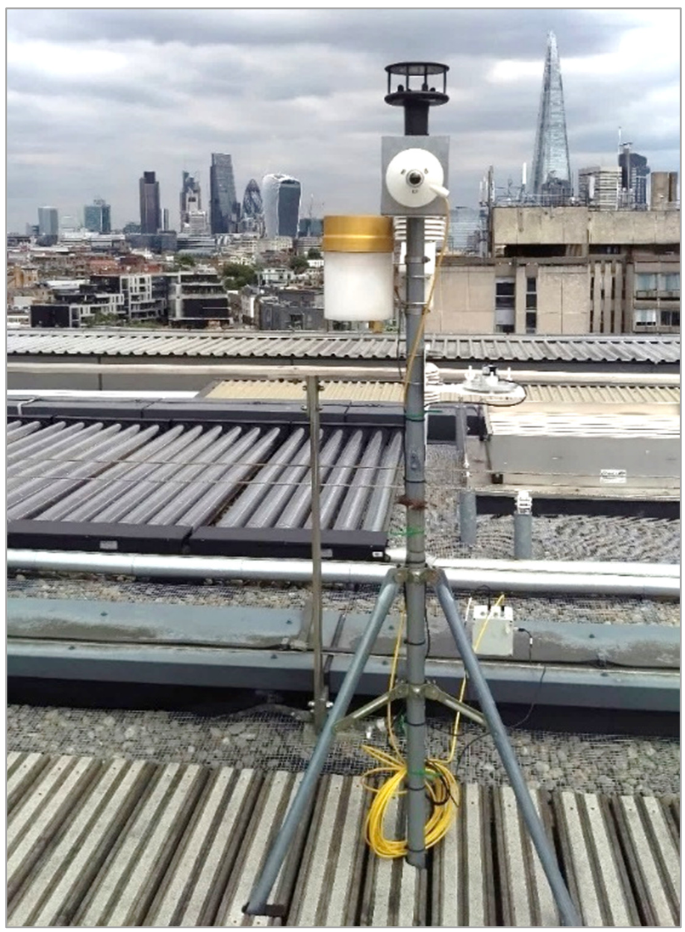


Figure 49. External Weather Station Set-up

Figure 50. Location Map of the External Weather Station

4.3.4.8 Focus Group

A focus group was used to capture additional information from the participants on their experience during testing and their thoughts on the robustness of the study design. This was held in week 9 (the week after the final test session) which enabled the participants' thoughts to be as fresh as possible. All participants were invited to participate, whether they had been taking part in the tests (i.e., completing the test batteries) or if they had just been present during the testing phase. They were advised that the focus group would take 60 minutes and that refreshments would be provided as an incentive to attend. Eleven out of the 19 participants attended the focus group, all of whom took part in the full study (completed the test batteries). Five participants attended from Office A and six participants attended from Office B.

A separate meeting room from the testing spaces was set up with the desks positioned in a horseshoe shape to allow for free-flowing conversations to take place between the participants. Two audio recording devices were set up at the rear and front of the room. The moderator was sat at a separate desk from the other participants at the front of the room. Minimal notes were taken by the moderator to encourage a more natural and open dialogue with the participants. The focus group was conducted in a semi-structured format with specific questions given to the participants. This allowed for more flexibility than structured interviews as it allowed for 'un-scripted' but relevant topics to be freely discussed as they arose in the natural dialogue.

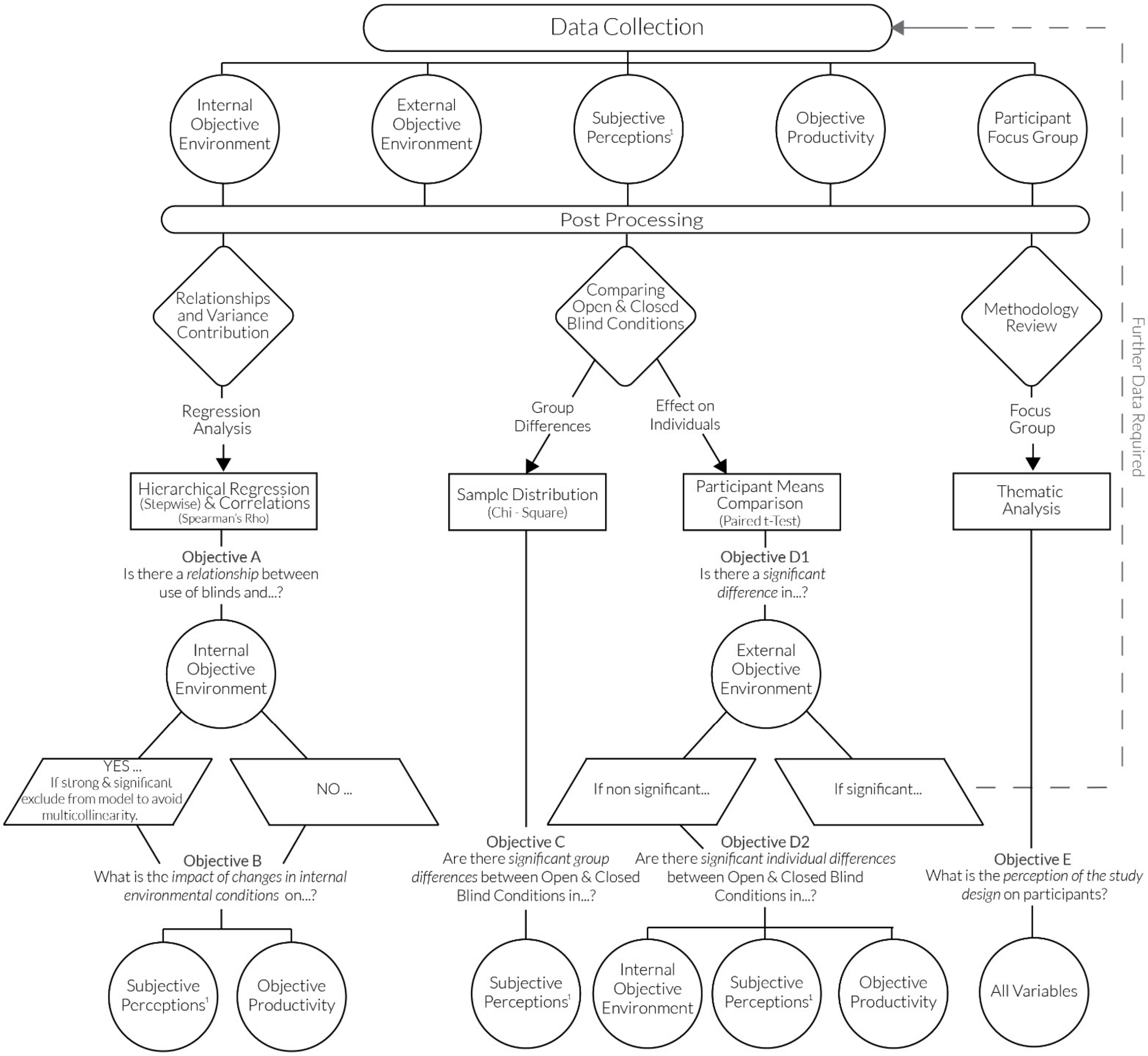
The scripted questions within the focus group were presented on slides with visual images as prompts to encourage any struggling or distracted participants to engage with the questions being discussed. The scripted questions are presented below:

1. Did the equipment installed impact you in any way during your day to day?
2. What did you think about the new blinds installed?
3. Did you find any of the interventions placed on the rooms challenging?
4. Were there any issues when completing the tests?
5. How relevant do you think the tests were to your day-to-day work activities?
6. Do you feel your performance on the tests differed between different test sessions?
7. How do you feel about the frequency and length of the tests?

The focus group was planned for at the start of the study. However, the specific questions were not scripted until mid-way through the study. During the test sessions, the researcher was provided with informal feedback from the participants about their experiences during testing when visiting the testing offices. These comments were used to form the focus group questionnaires in order to be able to better capture the ad-hoc data in a more robust method. This could provide important data in relation to the reliability of the study design.

4.4 Method of Analysis

Once all of the data was collected, the data was post-processed (checked for anomalies and smoothed). The process differed for each type of data collected and this process has been explained further in Appendix D. The internal and external environmental data was aligned with the test battery data collected for each participant by aligning the timestamps provided at the start and end of the test battery from the environmental dataloggers. The data from the closest internal environment sensor to each participant was averaged to give a singular mean environmental value for the duration of the test session for each test day. The same process was followed for the external environment data. These measures were individual to each participants' location and the time that each participant spent completing the test battery. The mean values were then reviewed to gain a better understanding of the overall data collected and the data was used in the analysis of each of the studies objectives (Objectives A – E) outlined in Figure 51. The statistical analysis was carried out using IBM SPSS Statistics 21.



[1] Subjective Perceptions include perceptions of the Internal Environment , Health & Well-being, Comfort & Productivity.

Figure 51. Analysis Framework

4.5 Results and Discussion

4.5.1 Overview of the Data Collected

Descriptive statistics were used to better understand the data collected across all of the test sessions. The objective data (or scale data) was evaluated so the minimum (Min), maximum (Max), mean (M), and standard deviation (SD) could be interpreted. The question data (or categorical data) was interpreted to identify the frequency of responses, as well as the modal response and establish the overall distribution of the data collected. This data has been presented using bar graphs. Each bar graph is titled referring to the question measure (which are listed in Table 20 - Table 25 (p. 132 - 141), Section 4.3.4.5.3 - 4.3.4.5.5). All the data presented in this section were collected across all of the test sessions when the participants were in either the blinds open or blind closed intervention and located in either Office A or Office B.

4.5.1.1 External Objective Environmental Data

Table 29 identifies the M, Min, Max, and SD for the 191 (N) mean external environmental data points collected. Each data point evaluated represents the mean external environmental condition over the duration of time that it took each participant to complete the tests and questionnaire (i.e., the test session mean for each participant). Table 30 analyses the same data but evaluates the M, Min, Max, and SD for each test session.

Table 29. Minimum (Min), Maximum (Max), Mean (M), and Standard Deviation (SD) of the external environmental data collected over the test sessions.

	N	Min	Max	M	SD
Vertical Solar Radiation (W/m^2)	191	59.86	316.20	192.34	57.75
Air Temperature (°C)	191	13.76	25.50	20.40	2.47
Horizontal Illuminance (klux)	191	17.01	99.96	49.896	20.51

The ranges (difference between Min and Max) in external illuminance and vertical solar radiation varied considerably across the test days (Table 29) and between the test days (Table 30). This data suggests that there were different levels of cloud cover between the test days, namely a mix of continuously clear days, continuously cloudy days, and days where the cloud cover was intermittent. CIBSE Guide A: Environmental Design Guide (CIBSE, 2015) provides mean values for typical weather conditions in London. These are based on the climate data collected from the London Weather Centre between 1996 - 2005. The mean values for vertical solar radiation levels and external air temperature for a south-west orientation for July and

Table 30.Minimum (Min), maximum (Max), mean (M) and standard deviation (SD) of the external objective environment during participants test sessions.

Date	Test Day*	N	Horizontal Illuminance (klux)				External Air Temperature (°C)				Vertical Solar Radiation (W/m²)			
			Min	Max	M	SD	Min	Max	M	SD	Min	Max	M	SD
13/07/2017	1	12	26.81	56.99	37.87	10.00	20.11	20.65	20.26	0.17	126.14	242.54	171.73	38.10
18/07/2017	2	16	96.54^{H}	99.97^{H}	98.57^{H}	0.72	24.14	24.58	24.33	0.11	241.87	316.20^{H}	261.62^{H}	19.26
20/07/2017	3	9	17.08	20.64^{L}	19.20^{L}	1.17	13.76^{L}	15.78^{L}	15.48^{L}	0.65	65.61^{L}	81.28^{L}	75.02^{L}	5.19
25/07/2017	4	15	52.81	61.74	54.93	2.58	18.56	19.10	18.77	0.15	214.60	253.78	221.15	10.54
27/07/2017	5	11	17.01^{L}	36.98	27.87	6.98	19.25	19.58	19.49	0.11	59.86	130.34	102.47	25.69
31/07/2017	6	15	17.80	80.27	63.35	14.32	21.12	21.92	21.60	0.23	103.61	279.44	232.98	41.28
03/08/2017	7	9	40.68	61.90	54.02	7.36	20.09	20.39	20.25	0.10	159.78	247.39	212.80	31.21
08/08/2017	8	15	43.86	56.84	47.73	3.99	17.35	17.57	17.46	0.06	172.72	236.33	191.24	19.64
10/08/2017	9	13	25.55	37.57	33.82	3.83	15.04	17.89	16.96	0.62	100.71	166.29	146.03	21.33
15/08/2017	10	13	63.40	73.73	66.94	3.60	21.87	22.49	22.03	0.17	245.41^{H}	314.78	261.88^{H}	22.37
17/08/2017	11	14	22.95	68.36	44.34	12.45	21.26	22.06	21.57	0.26	100.77	302.35	187.02	54.36
22/08/2017	12	14	27.90	35.86	31.89	1.89	21.06	21.73	21.28	0.19	124.45	160.77	142.91	7.99
24/08/2017	13	12	45.81	58.20	51.62	3.39	20.45	20.61	20.53	0.05	212.73	266.63	233.25	14.05
29/08/2017	14	10	37.02	45.05	40.66	2.44	25.12^{H}	25.50^{H}	25.37^{H}	0.12	162.87	195.58	177.22	10.13
31/08/2017	15	13	24.10	70.54	49.21	14.16	18.55	19.73	19.48	0.31	107.48	276.54	199.95	48.99

^{H} = Highest measurement across all test days, ^{L} = Lowest measurement across all test days. *For Test Days 1 and 15, the blinds were closed in both offices (A&B) and for Test Days 2 – 14, the blinds were either open or closed and alternated between Office A and B.

August were 175 W/m^2 and 195 W/m^2, and 19°C and 17.6°C, respectively. In this study, the external temperatures were 1.4 - 2.8°C higher than the mean temperatures and the level of vertical solar radiation was between the mean values provided by CIBSE (2015). The observed increase in external temperatures is likely to be a result of the urban heat island effect which has continued to increase external air temperatures since these typical weather condition data were collated. The range in external weather conditions that were experienced when the study was conducted can be considered as above average when compared to the typical weather data collected between 1996 - 2005 (CIBSE, 2015).

Table 30 identifies that on Test Day 3, the mean external air temperature (15.48°C), illuminance (19.2 klux), and solar radiation (262 W/m^2) received vertically was the lowest. This occurred when Office A blinds were open and Office B blinds were closed. Test Day 2 experienced the highest mean level of illuminance externally, specifically 98.57 klux, and Test Day 14 was the warmest, with a mean air temperature of 25.4°C. On Test Days 2 and 10 the largest mean amount of vertical solar radiation was recorded of 262 W/m^2. This occurred when Office A blinds were closed, and Office B blinds were open. The differences in the external conditions meant that to fairly analyse the data, the data of both offices needed to be grouped and assessed between the interventions (blind open and blind closed) as opposed to making comparisons between the offices and the interventions. The similarity in office layout and design between the offices made this possible.

4.5.1.2 Internal Objective Environment Data

Table 31 identifies the M, Min, Max, and SD for the mean internal environment data collected. Each data point (N) represents the mean internal environmental condition over the duration of time that it took each participant to complete the tests and questionnaire.

Table 31.Minimum (Min), Maximum (Max), Mean (M), and Standard Deviation (SD) of the internal environmental conditions.

	N	Min	Max	M	SD
Lux (klux)	185	114.59	1039.80	474.04	258.70
Operative Temperature (°C)	168	25.58	39.13	33.82	2.97
Air Temperature (°C)	185	22.24	28.52	25.42	1.60
Relative Humidity (%)	185	39.69	61.30	53.69	5.06
CO_2 (PPM)	165	433.52	2222.64	1174.52	468.45
Noise (dBA)	185	39.70	53.13	44.13	1.89

The number of data points collected and analysed (N) for each internal objective environmental measurement in Table 31 differ because of various data logging issues that occurred during the data collection period. The factors that affected the data collection are explained in Appendix E. However, this did not affect the analysis as the N was sufficient for the various statistical analysis techniques used.

Table 31 shows that the range of illuminance, operative temperature, and CO_2 levels experienced ranged both above and below the recommended comfort thresholds[30]. The operative temperatures and noise levels (dBA) were consistently over the recommended fixed comfort thresholds (25°C for summer and 35 dBA for offices), and the relative humidity remained at comfortable levels (40 - 70%). This identifies that the offices were overly warm for the duration of the testing period, that they were relatively noisy, and that there was a broad variation in illuminance and CO_2 levels. The relative humidities can be considered typical although they spanned a relatively narrow range. Therefore, the results of this study are only relevant to these conditions.

The noisy acoustic conditions are a consequence of the location of the offices. The offices were exposed to continuous road traffic noise as they are located next to a main road in London. The occupants within the space were more conventionally used to even louder conditions as the windows were usually opened to ventilate the offices. Closing windows was incorporated into the study design to reduce the variation in internal air velocities and noise conditions. This subsequently contributed to the overly warm internal temperatures experienced.

Even though the operative temperature conditions exceeded the recommended fixed operative temperature threshold (25°C for summer) (CIBSE, 2015), when reviewing the operative temperatures in relation to the maximum acceptable operative temperature threshold, $\Theta_{max,}$[31], the operative temperatures in this study were both recorded above and below the adaptive threshold (see Appendix F for calculations of the Θ_{max}).

The measured air temperatures suggest that they were still within the boundaries of when occupants are believed to perform at their best (between 22 - 24°C). This was identified in a meta-analysis of various productivity-related research studies (Seppänen et al., 2006). The two measures used to monitor internal temperature (operative and air temperature)

[30] Comfort thresholds: lux level (300 - 500 lux on the work plane), operative temperature (22 - 25°C), air temperature (no set threshold), relative humidity (40 - 70% RH), CO_2 levels (950 - 1250 ppm), and noise levels (30 dBA).
[31] This gives a more accurate prediction of adaptive thermal comfort by considering the previous day's external weather conditions, T_{rm}, and a person's ability to adapt to internal environments.

differed by a mean of 8°C. Considering that the kata thermometer measurements confirmed that the internal air velocities were low < 0.1 m/s and relatively stable when the temperature data were collected (see Section 4.3.4.6.2, p. 158), we can assume that the mean radiant heat from the various internal and external sources (occupants, lighting and equipment, thermal mass of the building and furniture, and solar radiation) caused the difference between the two temperature measurements. This is because operative temperature considers the effect of air temperature, mean radiant temperature, and air velocity on a black globe (representative of a person) (CIBSE, 2015).

4.5.1.3 Subjective Perceptions of the Internal Environmental Questions

Thermal Comfort

Figure 52 shows that the participants' perception of the air temperature were relatively normally distributed and the modal response suggests that the majority of participants perceived the conditions as 'Slightly Warm'. The two other thermal comfort measures were negatively skewed, suggesting that the participants preferred cooler conditions. These conditions were believed to be 'Just Unacceptable' (N = 80) or 'Acceptable' (N = 79) overall. The participants' thermal preference and acceptability responses appear logical in respect of their thermal sensation response. Generally, it is thought that as occupants perceive warmer conditions, they will be perceived as less acceptable and prefer cooler conditions. The results also suggest that the participants were appropriately identifying the overly warm conditions.

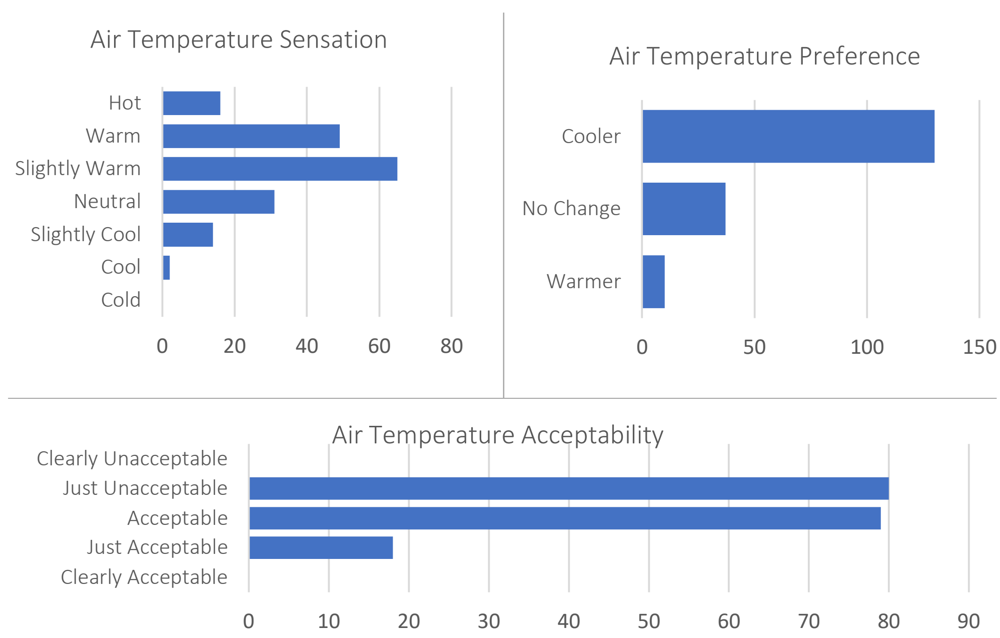


Figure 52. Frequencies of the Thermal Comfort Measures across all Test Sessions (N = 177)

Air Quality

Figure 53 identifies that the participants' perceptions of air humidity and air odour were normally distributed. The modal response suggests that the conditions were 'Slightly Humid' and 'Neither Pleasant nor Unpleasant' odours or fragrances were experienced. The participants' perception of the air freshness was positively skewed, suggesting that the conditions were often 'Stuffy'. The distributions for how the participants would prefer the air quality to be were also skewed towards a preference for 'Drier', 'Fresher', and 'More Pleasant Odours'.

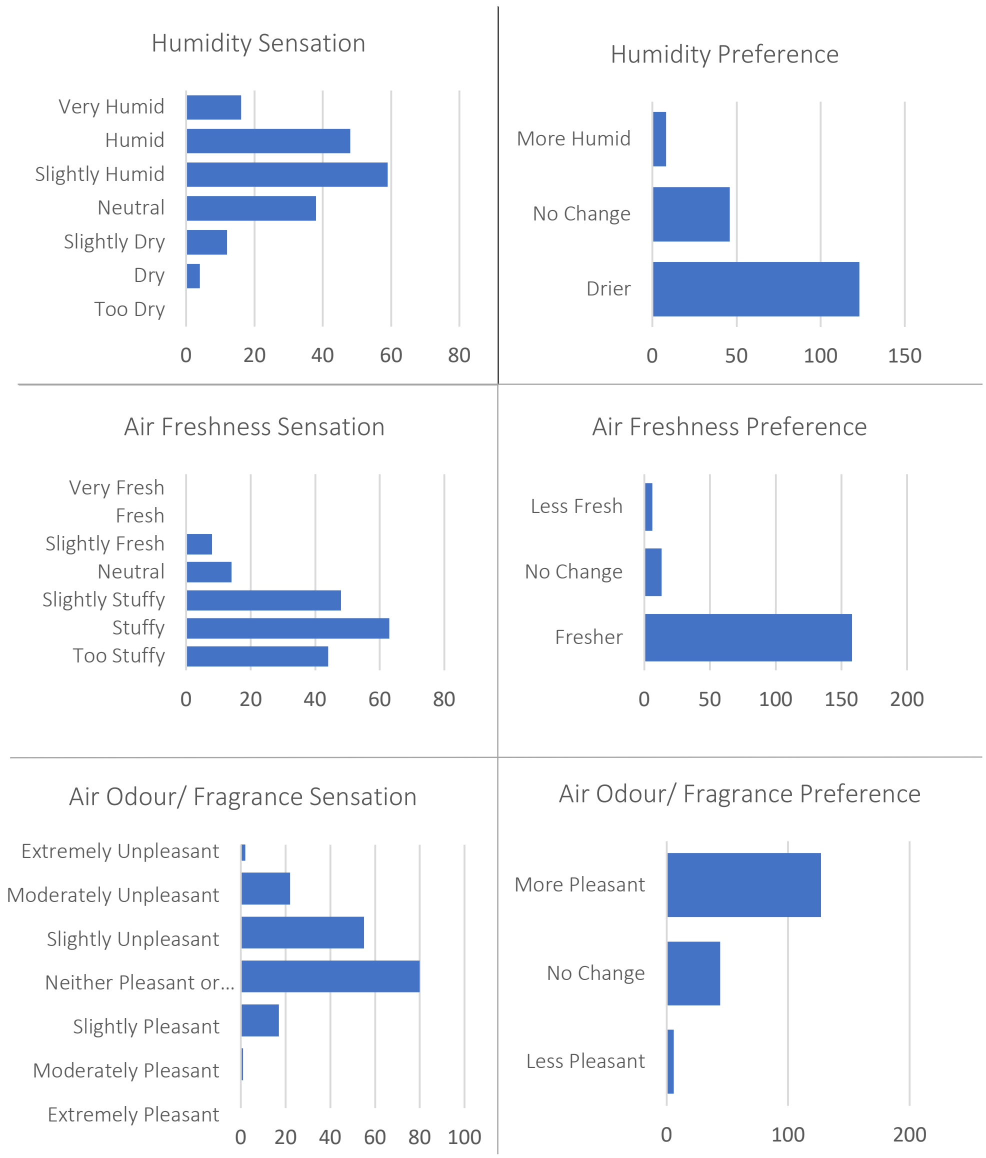


Figure 53. Frequencies of the Air Quality Measures across all Test Sessions (N = 177)

Considering that the windows were closed during the test sessions, these results are unsurprising as the low air velocities and the lack of fresh air entering the offices would have negatively affected the perceptions of air quality overall. Interestingly a small number of responses related to more positive responses (e.g., 'Slightly Fresh' and 'Slightly Pleasant') which suggests that individuals reacted differently to the conditions on certain test days. When reviewing the range of responses reported by each participant to the Air Freshness Sensation question, some reported responses between 'Slightly Fresh' and 'Too Stuffy' (a response range of 5) while others reported a much narrower range of responses. The lowest being a response range of 2 between either 'Too Stuffy' and 'Stuffy', 'Stuffy' and 'Slightly Stuffy' or 'Slightly Stuffy' and 'Neutral', identifying that some of the participants consistently felt that the air quality was poor.

Visual Comfort

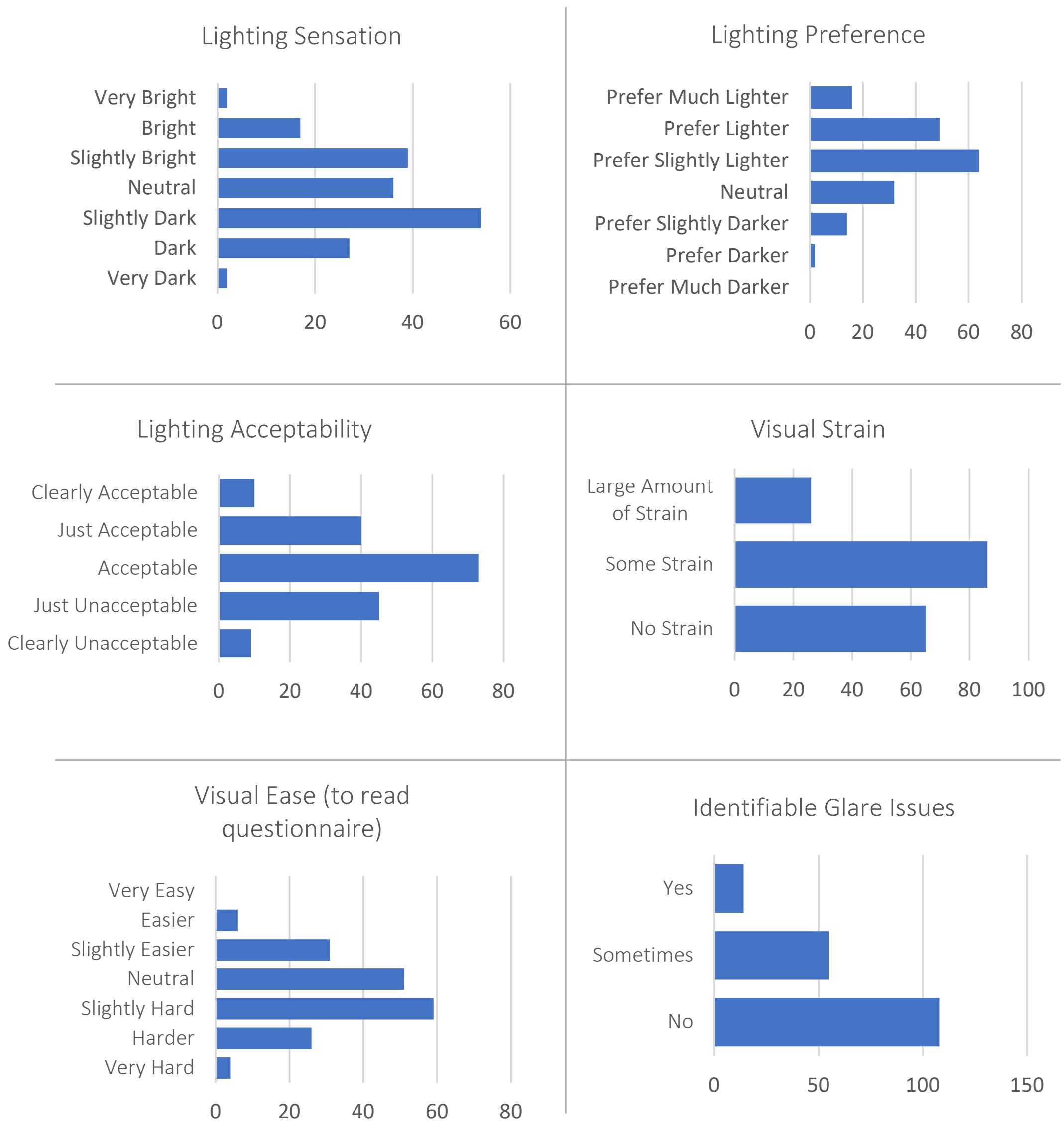


Figure 54. Frequencies of the Visual Comfort Measures across all Test Sessions (N = 177, part 1 of 3)

All of the measures for visual comfort, presented in Figure 54, were either normally distributed or had relatively symmetric distributions with the exception of when the participants were asked if they were experiencing glare (Glare Issues Identified). The modal responses suggest that the participants felt that the offices were 'Slightly Dark'. The participants had a preference for 'Slightly Lighter' conditions but overall, they determined the conditions to be 'Acceptable'. The majority of participants found the questionnaire 'Slightly Hard' to read. The level of brightness caused 'Some Strain' when reading the questionnaire and the majority of participants did not experience any glare issues during the test sessions. There were 69 instances where participants experienced glare issues during the test sessions (identifiable from the 'Yes' or 'Sometimes' response in Figure 54 to the Identifiable Glare Issues question) and these participants were then asked further questions regarding the glare they perceived. The results of these questions are presented in Figure 55.

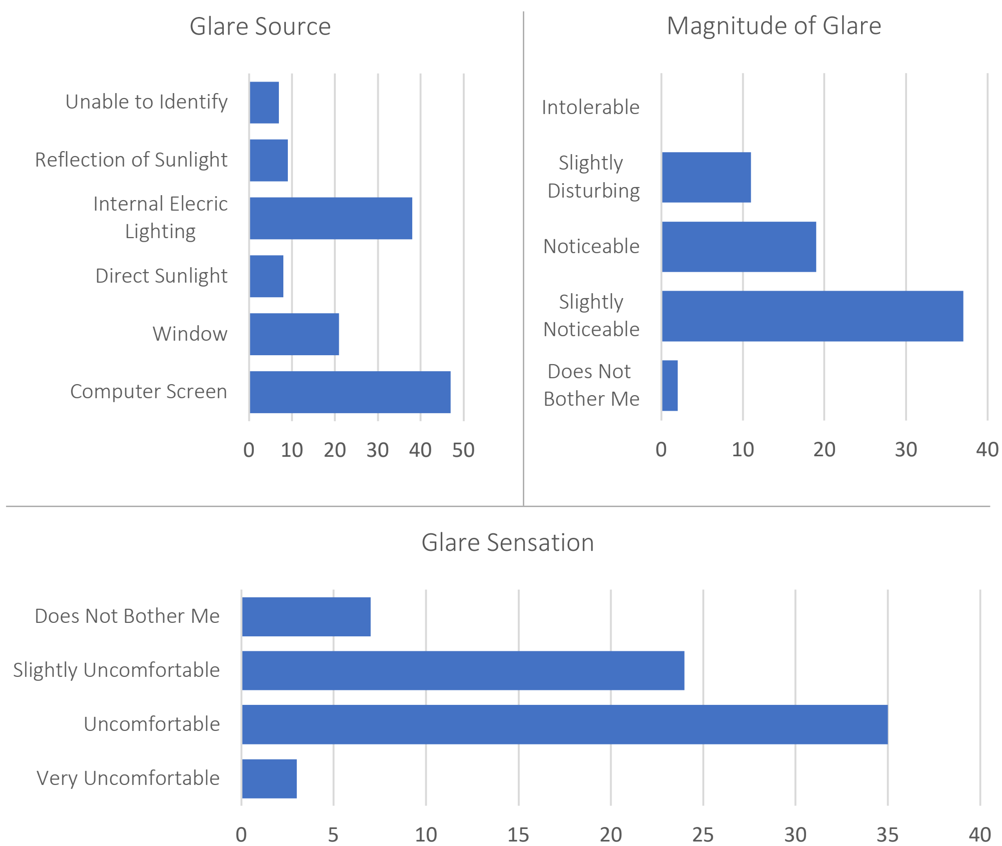


Figure 55. Frequencies of the Visual Comfort Measures across all Test Sessions (N = 69 and 130[32], part 2 of 3)

The participants' perceptions of the magnitude of the glare were skewed with the modal response identifying that overall, the glare identified was 'Slightly Noticeable'. The responses given about how participants felt about the glare had a symmetrical distribution

[32] Multiple responses could be provided for the 'Glare Source' question.

and the modal response identified that the glare experienced made the participants feel 'Uncomfortable'. When the participants were asked to identify the source of the glare, the most frequent response given was 'Computer screens' (N = 47) followed by 'Internal Electric Lighting' (N = 38). This was a surprising finding considering that the participants were either in rooms with blinds permanently closed or open. It was expected that the main cause of glare would have been caused by 'Direct Sunlight', 'Reflection of Sunlight' or potentially the 'Window'. This unusual finding is further interrogated when comparing the participant responses between the interventions in Section 4.5.4 (p. 229).

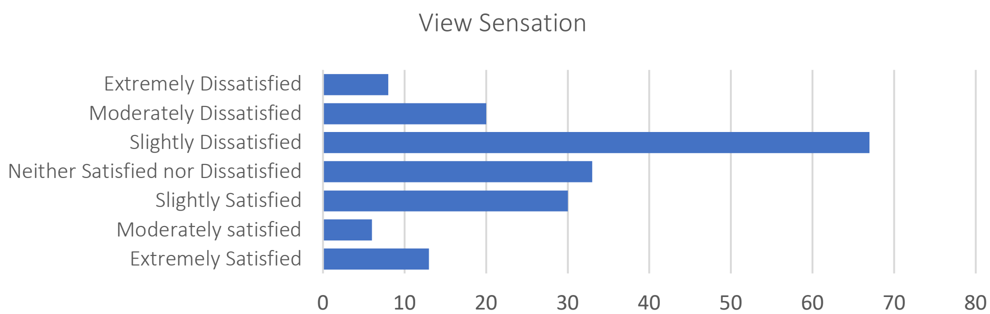


Figure 56. Frequencies of the Visual Comfort Measures across all Test Sessions (N = 177, part 3 of 3)

When the participants were asked how satisfied they were with their view (Figure 56), the responses were relatively normally distributed. The modal response identified that most of the participants were 'Slightly Dissatisfied' with their view. Seven out of the nineteen participants were positioned directly next to a window. However, all participants would have had some sort of access to a view out of a window no matter where they were positioned within the office. The view out of the south-west window provided views of a busy street, lined with houses and businesses with some large trees planted along the street (Figure 57). Those on the north-west façade looked out onto a mainly concrete courtyard with some planting. Both views provided a view of the skyline.

Figure 57. Views with (Top) and without shading (Bottom) out of south-west windows in Office A.

__Acoustic Comfort__

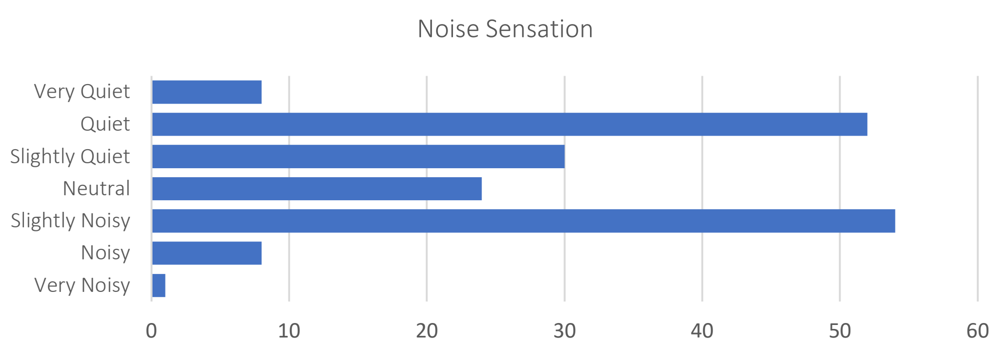


Figure 58. Frequencies of the Acoustic Comfort Measure across all Test Sessions (N = 177)

The participants' perception of the noise levels was bimodally distributed (Figure 58). The peaks identify that most of the participants felt that the office was either 'Quiet' (N = 52) or 'Slightly Noisy' (N = 54). The mean internal acoustic conditions varied by 13 dBA (difference between the Min and Max, Section 4.5.1.2, Table 31 (p. 165) and although this suggests there was a relatively small amount of difference in dBA experienced across the test sessions, a change of 10 dB can be perceived as half as loud (Goelzer et al., 2001).

Therefore, this change in sound may have been noticed by some of the participants between the test sessions. Overall, these results suggest that the participants' perceptions of the loudness of the sound differed across the test sessions.

4.5.1.4 Subjective Comfort and Productivity Questions

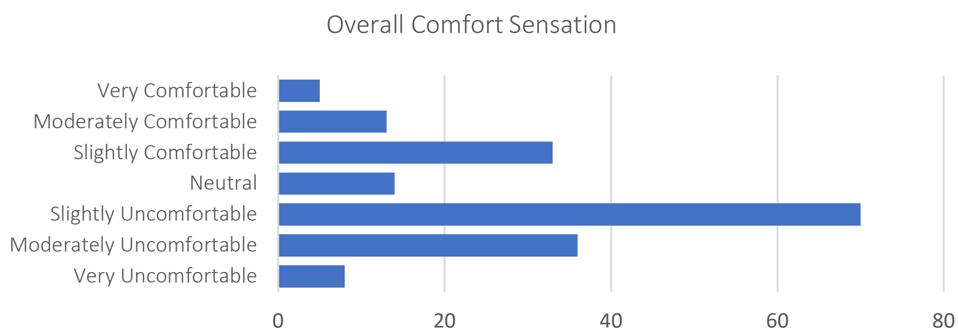


Figure 59. Frequencies of the Comfort Measure across all Test Sessions (N = 179)

Figure 59 displays the distribution of the responses to the overall comfort measure which were slightly bimodal with peaks representing 'Slightly Comfortable' and 'Slightly Uncomfortable'. The latter being the mode response. The bimodal response suggests that the individual participants' perceptions of how comfortable the office spaces were varied across the test sessions.

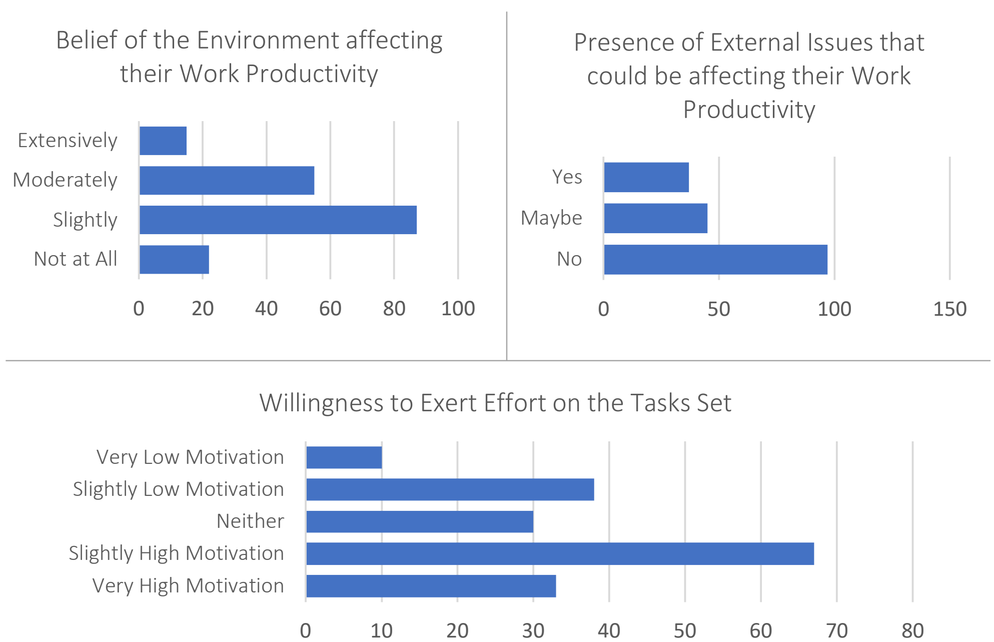


Figure 60. Frequencies of the Subjective Productivity Measures across all Test Sessions (N = 178 to 179)

A normal distribution was found with a modal response of ‘Slightly’ when the participants were asked whether they believed that the indoor environment was affecting their work productivity (Figure 60). A skewed distribution was found when the participants were asked whether they believed if anything outside of the work environment was affecting their work productivity with the most frequent response being ‘No’ (N = 97). However, the other options ‘Yes’ and ‘Maybe’ totalled an N of 82. This identifies that 46% of the participants believed that something other than the internal environmental conditions was affecting their work productivity. Lastly, when the participants were asked how motivated they felt to complete the tasks set, the majority identified they had a ‘Slightly High’ (N = 67) willingness to exert effort on the tasks set.

4.5.1.5 Health and Well-being Questions

All participant responses to the pre-test health and well-being measures are presented in Figure 61. All measures were positively skewed towards a ‘Not at all’ response apart from the responses to the two questions given before the objective productivity tests which asked how tired the participants felt. It also asked them to describe their level of fatigue. The responses to these questions were normally distributed. The modal response for the Feeling Tired question suggests that most of the participants felt ‘Slightly Tired’. This corresponds with the mode response of ‘A little tired’ in the Description of Fatigue question.

Figure 61. Frequencies of the Health and Well-being (Pre-Test) Measures across all Test Sessions (N = 179)

All participant responses to the post-test health and well-being measures are presented in Figure 62 - Figure 65. The distribution of the measures were either symmetric, relatively symmetrical, or skewed in their distribution. Due to the large number of measures, the modal responses for each question have been summarised in Table 32.

Table 32. Mode response of Post-test Health and Well-being Questionnaire (N = 177)

Question Measure	Overall Mode Response
Nose: Clear or Blocked?	Very Clear
Nose: Dry or Running?	Very Dry
Mouth: Dry or Running?	Slightly Dry
Lips: Dry or Not Dry?	Slightly Dry
Skin: Dry or Moist?	Neither Dry or Moist
Hair: Dry/Brittle or Not Dry/Brittle?	Neither Dry/Brittle or Not Dry/Brittle
Nails: Brittle or Supple?	Neither Brittle or Supple
Eyes: Dry or Not Dry?	Slightly Dry
Eyes: Smarting/Hurting or Not Smarting/ Hurting?	Slightly Smarting
Eyes: Aching or Not Aching?	Neither Aching or Not Aching
Eyes: Feel Gritty or Not Gritty?	Neither gritty nor not gritty
Headache Symptoms	(Definitely) No Headache
Clarity of Thinking	Slightly Difficult to Think
Dizziness Sensation	Not Very Dizzy
General Feeling	Neither Good or Bad
Tiredness (Post-test)	Slightly Tired
Ability to Concentrate	Slightly Difficult to Concentrate
General Attitude	Neither Depressed or Positive
Alertness	Slightly Sleepy
Office Cleanliness	Slightly Dusty/Dirty
Mental Demand Required	Slightly High
Physical Demand Required	Very Low
Pace of the Tasks	Neither Hurried nor Slow
Successfulness in completing the Tasks Set	Slightly High
Amount of Effort required to achieve level of performance on the Tasks Set	Slightly High
Feeling Insecure when completing the Tasks Set	Neither High nor Low
Feeling Discouraged when completing the Tasks Set	Very Low
Feeling Irritated when completing the Tasks Set	Very Low
Feeling Stressed when completing the Tasks Set	Very Low
Feeling Annoyed when completing the Tasks Set	Very Low

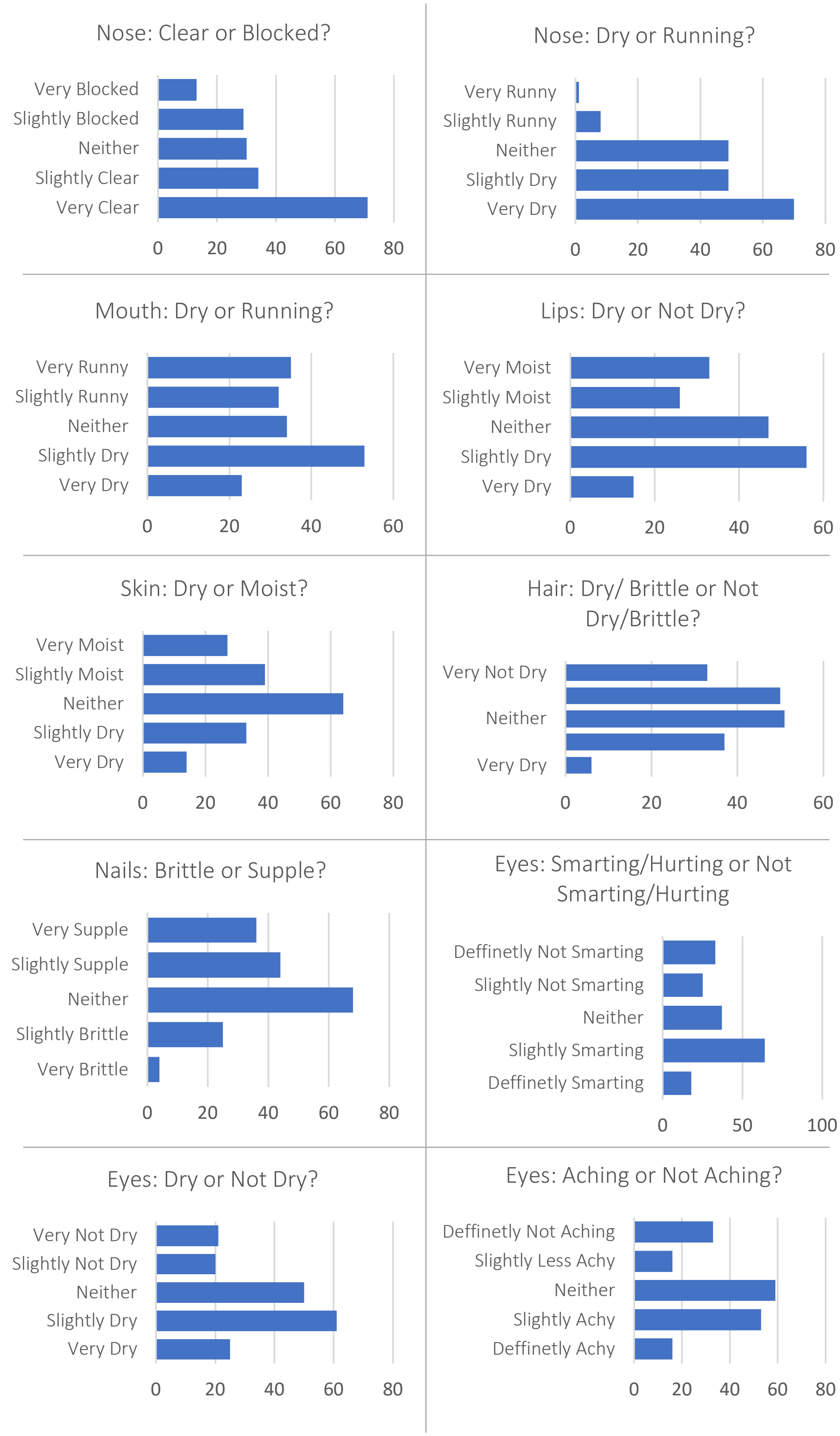


Figure 62. Frequencies of the Health and Well-being (Post-test) Measures across all Test Sessions (N = 177, part 1 of 4)

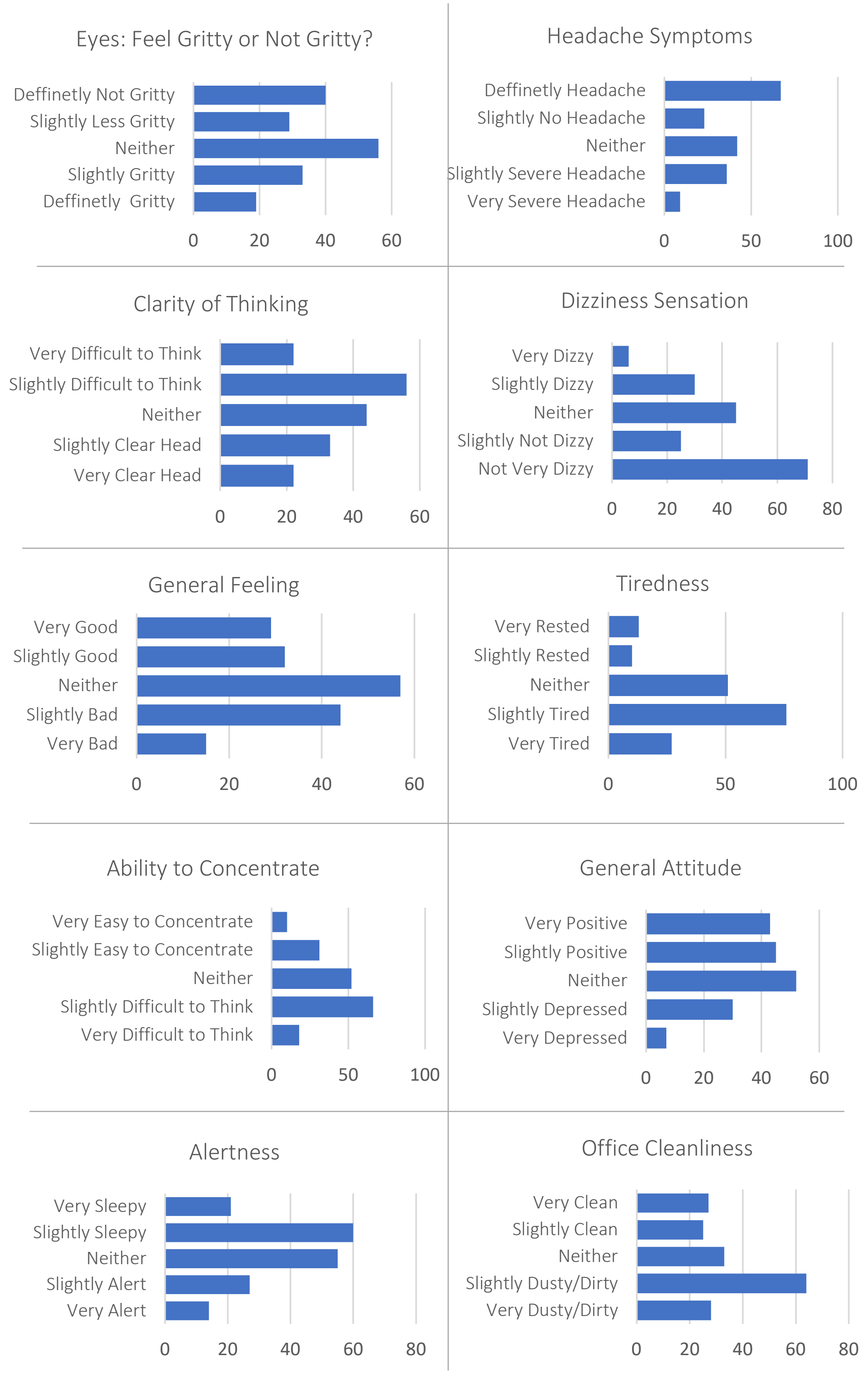


Figure 63. Frequencies of the Health and Well-being (Post-test) Measures across all Test Sessions (N = 177, part 2 of 4)

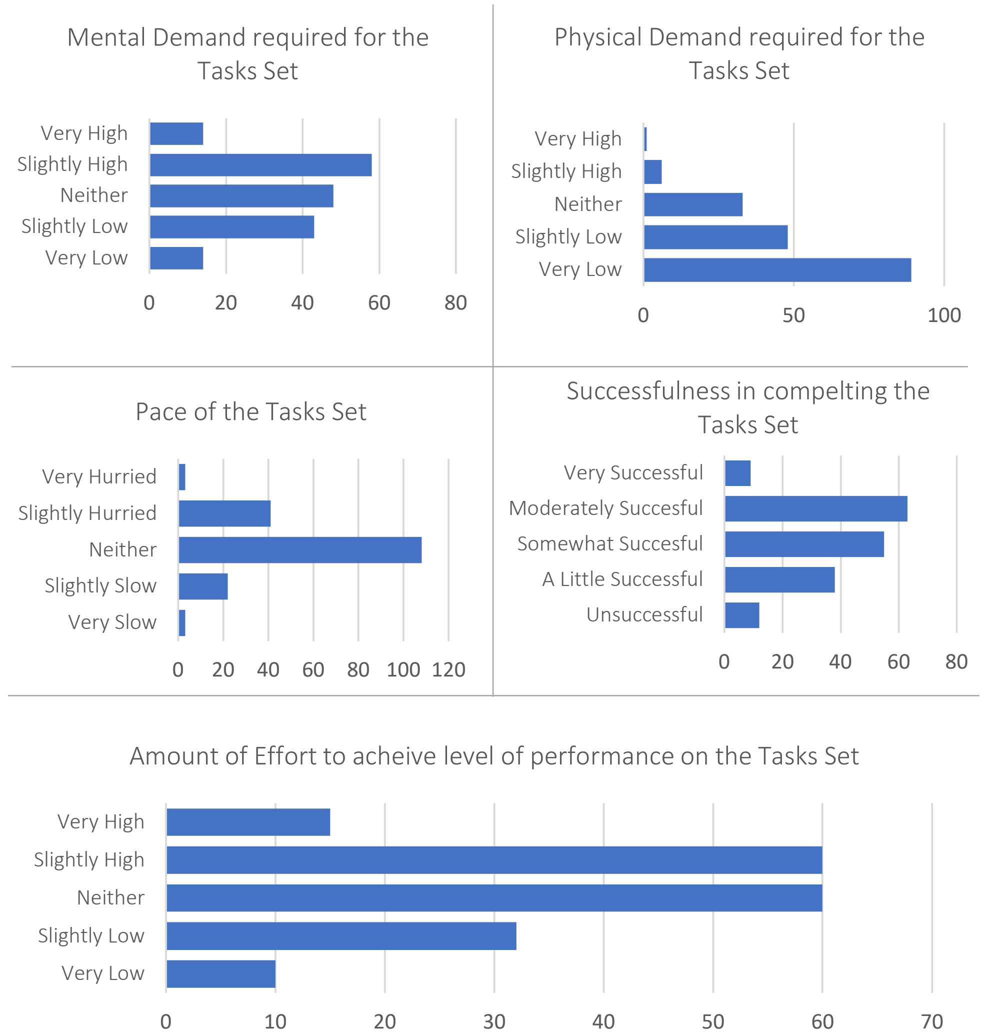


Figure 64. Frequencies of the Health and Well-being (Post-test) Measures across all Test Sessions (N = 177, part 3 of 4)

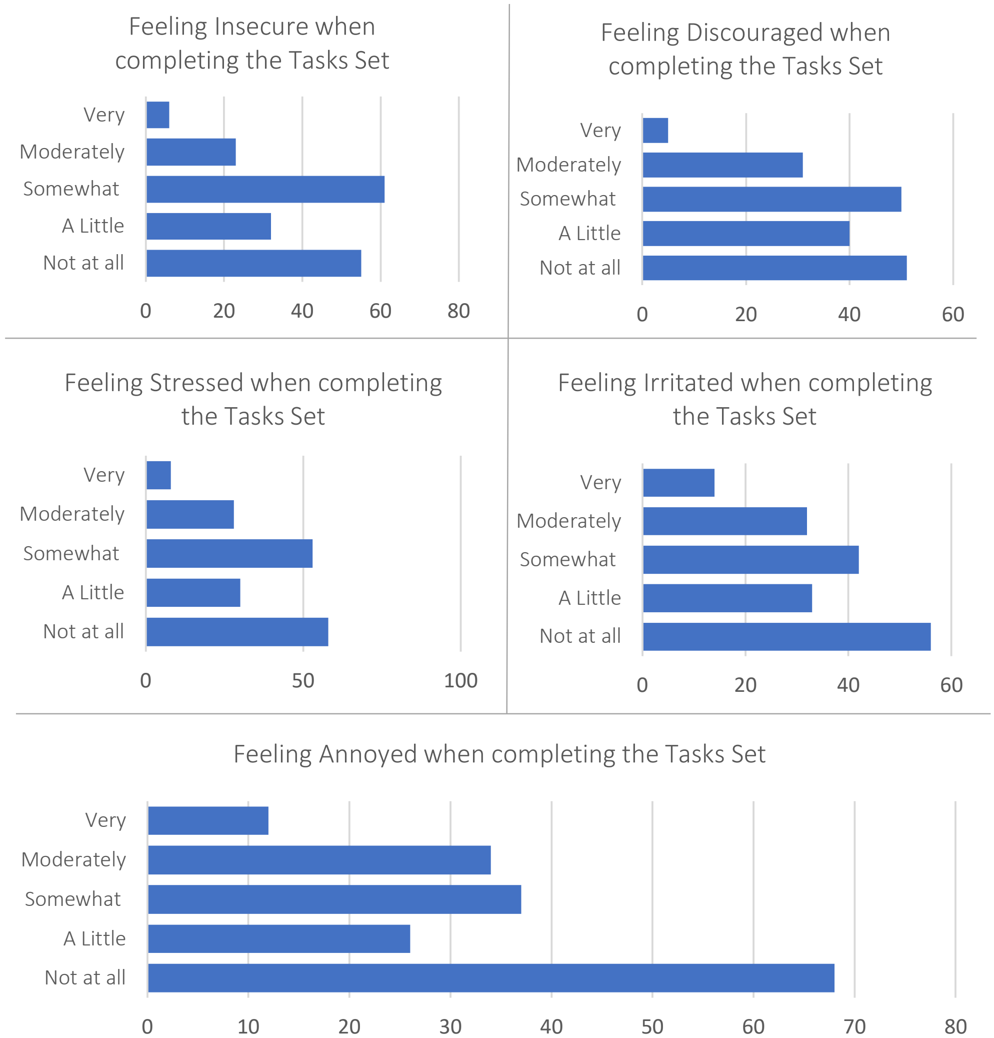


Figure 65. Frequencies of the Health and Well-being (Post-test) Measures across all Test Sessions (N = 177, part 4 of 4)

4.5.1.6 Objective Productivity

Table 33 and Table 34 identifies the Min, Max, M, SE, and SD values for the objective productivity test scores. The work type test data are presented in Table 33 and the cognitive function test data are presented in Table 34.

Work Type Tests

The average number of words typed was 45 words per minute (WPM). This is slightly lower than the average person (50 WPM). However, non-trained typists typically average 5 WPM lower than the average trained typist (Dhakal et al., 2018). The number of errors made on the Text Typing test were low, ranging between 0 and 9 with a mean of 2.48 which suggests a skewed distribution of data with the majority of participants making very few errors. This contributes to why the Text Typing Accuracy scores were positively skewed (M = 94.57).

Table 33.Minimum (Min) and Maximum (Max), Mean (M), Standard Error (SE), and Standard Deviation (SD) of the responses to the Work Type Tests.

	N	Min	Max	M	SE	SD
TEXT TYPING - *No. of words typed per minute*	189	14.00	71.00	44.74	0.84	11.52
TEXT TYPING - *No. of errors made*	189	0.00	9.00	2.48	0.16	2.21
TEXT TYPING - *Accuracy of words typed (%)*	189	80.00	100.00	94.57	0.34	4.63
ARITHMETIC - *Task switching speed (s)*	177	-141.25	148.42	15.92	2.30	30.64
ARITHMETIC - *Task switching accuracy (%)*	177	25.00	100.00	90.36	1.22	16.17
DATA CHECKING - *No. of questions answered*	175	3.00	20.00	11.98	0.23	3.07
DATA CHECKING - *No. of correct answers*	175	0.00	17.00	8.39	0.30	4.00
DATA CHECKING - *Accuracy (%)*	175	0.00	100.00	69.31	2.14	28.27
GRAMMAR – *No. of correct answers*	177	46.67	100.00	78.76	0.81	10.81

The negative minimum result in the Arithmetic (Task Switching Time) test identifies that the participants had an issue with this test as only positive results should have been recorded. During the focus group, which was used to identify issues in the study design, it was revealed that some of the participants failed to press enter at the end of each section of questions completed on screen, distorting the results[33]. Therefore, the Arithmetic Test has not been analysed further.

The number of correct answers (M = 8.39) and the accuracy (M = 69.31) in the Data Checking Test and the number of correct answers (M = 78.76) in the Grammar Test had normal distributions but were slightly positively skewed. The minimum score of 0 on the Data Checking Test for the number of correct answers and the accuracy score indicates that some of the participants either struggled with the test or did not put effort into completing the task.

Cognitive Function Tests

The time taken to complete the Number Search test was normally distributed as were all of the measures for the Reaction Time and Processing Speed tests and the Long and Short-Term Memory tests. The participants' accuracy in the Number Search test (M = 0.81) and all of the Processing Accuracy (Stroop) measures were positively skewed, indicating that a

[33] Descriptive statistics relating to the Arithmetic Test were supported by the focus group analysis (see Appendix I, *Line 137 - 149*). Therefore, the decision was made that these results were not reliable to include within the analysis due to the poor performance of the test battery.

ceiling effect may have been reached over the duration of the test sessions. The Working Memory test was also positively skewed (M = 5.53). The average performance in this test for adults is a score of 4 – 5. This suggests that this population sample was slightly better (M = 5.53) than average. However, as the maximum score on the Working Memory task was reached (Max = 8), we can assume that there was a ceiling effect. This may have been caused by participants cheating on the test. For example, a participant admitted to writing down answers on the working memory test in the focus group (see Section 4.5.6.1., p. 279). This participant's working memory test data were removed from the data set prior to analysis.

Table 34.Minimum (Min) and Maximum (Max), Mean (M), Standard Error (SE) and Standard Deviation (SD) of responses to the Cognitive Function.

	N	Min	Max	Mean	SE	SD
NUMBER SEARCH - *Accuracy of responses (%)*	177	0.00	1.00	0.81	0.03	0.40
NUMBER SEARCH - *Time taken to respond (s)*	177	0.00	29.98	15.25	0.28	3.79
REACTION TIME – *Mean time to answer correctly (s)*	177	0.43	1.69	0.54	0.01	0.12
REACTION TIME - *Mean Time to answer incorrectly (s)*	177	0.00	1.77	0.19	0.02	0.27
REACTION TIME - *Mean time to provide all responses (s)*	177	0.38	1.69	0.55	0.01	0.15
PROCESSING SPEED (STROOP) - *Mean time to respond to control stimuli (s)*	177	0.57	2.20	0.89	0.02	0.21
PROCESSING SPEED (STROOP) - *Mean time to respond to incongruent stimuli (s)*	177	0.64	2.32	1.10	0.02	0.32
PROCESSING SPEED (STROOP) - *Mean time to respond to congruent stimuli (s)*	177	0.58	2.09	0.88	0.02	0.22
PROCESSING ACCURACY (STROOP) - *Accuracy of responses to control stimuli (%)*	177	81.75	100.00	98.55	0.19	2.56
PROCESSING ACCURACY (STROOP) - *Accuracy of responses to incongruent stimuli (%)*	177	0.00	100.00	91.42	1.47	19.55
PROCESSING ACCURACY (STROOP) - *Accuracy of responses to congruent stimuli (%)*	177	81.50	100.00	98.17	0.24	3.24
SHORT TERM MEMORY - *No. of correct answers*	177	0.00	1.00	0.54	0.04	0.50
WORKING MEMORY - *No. of digits recalled correctly*	177	0.00	8.00	5.53	0.15	1.93
LONG TERM MEMORY - *No. of correct answers*	177	0.00	19.00	6.30	0.26	3.49

4.5.2 Relationship Between Blind Position and the Internal Objective Environment Measures (Objective A)

A Spearman's Rho correlation matrix was produced to investigate whether there was a relationship between blind position (open or closed) and the internal objective environment (Objective A). This section also explores the other relationships found between the internal objective environment measures (i.e., illuminance, relative humidity, CO_2 levels, noise levels, and temperature). Table 35 presents the results of the correlation where several significant ($p < 0.05$) and highly significant relationships ($p < 0.01$) were found between the internal environment conditions and blind position. A description of the outputs of the Spearman's Rho correlation matrix is provided below, followed by a description and discussion of the significant ($p < 0.05$) results presented in Table 35. The significant results are highlighted in bold in Table 35.

Spearman's Rho Correlation

This statistical method identifies what relationships there are between two variables and it informs us of their strength (strong or weak), including whether they are positively or negatively correlated and the significance of these relationships. A strong relationship is identified if the $r_s \geq 0.8$. The strongest relationship possible is a relationship of 1 which would mean that as one variable increases by one, the other variable would also increase by one. A weak relationship is found when the $r_s \leq 0.3$. The polarity of the integer of the r_s defines the direction (positive or negative) of the relationship and the statistical significance of the r_s identifies the probability of the relationship being found by chance. A low probability ($p < 0.05$) suggests that the results were not found by chance (Dancey and Reidy, 2002).

Table 35.Spearman's Rho rank-correlation of Internal Objective Environment Measures.

Spearman's Rho Rank Correlation Matrix (r_s)							
		1	2	3	4	5	6
1	Illuminance (lux)	-	-	-	-	-	-
2	Relative Humidity	0.04	-	-	-	-	-
3	CO_2	-0.12	**0.30****	-	-	-	-
4	Noise (dBA)	0.08	**-0.27****	-0.09	-	-	-
5	Air Temperature	**0.18***	-0.06	0.01	-0.03	-	-
6	Operative Temperature	**0.21****	-0.01	0.01	-0.08	**0.89****	-
7	Blind Position	**0.83****	**0.23****	0.06	0.01	0.13	**0.16***

Note: Coefficients represent a varied sample size (N = 152 to 185), and significant results are highlighted in bold with * *p < 0.05* ** *p < 0.01*. Blind Position was coded as 0 = Closed and 1 = Open.

4.5.2.1 Blind Position and the Internal Objective Environment Measures

A strong positive correlation was found between lux level and blind position ($r_s = 0.83$, $p < 0.01$). A weak positive correlation was found between blind position and relative humidity ($r_s = 0.23$, $p < 0.01$), as well as blind position and operative temperature ($r_s = 0.16$, $p < 0.05$). This suggests that when the blinds were closed, the lux levels ($r_s = 0.83$, $p < 0.01$), relative humidity ($r_s = 0.23$, $p < 0.01$), and operative temperature ($r_s = 0.16$, $p < 0.05$) increased when the blinds were open and decreased when the blinds were closed.

The previous research agrees that closing the blinds will attenuate the daylight and decrease the internal temperatures when the buildings windows are exposed to solar radiation (CIBSE, 2015; ES-SO, 2018; Littlefair, 2017; Seguro and Palmer, 2016). However, surprisingly no relationship was found between blind position and air temperature, although there was a strong positive relationship between air and operative temperature ($r_s = 0.89$, $p < 0.01$). Operative temperature was found to be positively correlated with blind position ($r_s = 0.16$, $p < 0.05$). This implies that there was an indirect relationship between air temperature and blind position, and it also indicates that when the blinds were closed, the internal air temperatures may have decreased.

The relationship found between blind position and relative humidity ($r_s = 0.23$, $p < 0.01$) has not been identified in the previous research literature. Relative humidity is a function of air temperature and how much water vapour there is in the air. Increases in air temperature increase the capacity of the air to hold moisture. If the air temperature rises and the water content stays constant, the relative humidity will decrease (Sciencing, 2017). For relative humidity to increase when the blinds were open, either the water content in the air and the air temperature increased or the air temperature decreased and the water content in the air remained the same. Considering having the blinds open increased the operative temperature (which is positively related to an increase in air temperature ($r_s = 0.89$, $p < 0.01$)). We can hypothesise that the water content and the air temperature in the room must have increased for a significant positive relationship to be found between blind position and relative humidity. The water content may have increased in the air due to rainfall (which occurred on some test days but was not recorded) or because the occupants' respiration and perspiration increased in the warmer temperatures that they experienced when the blinds were open. Alternatively, relative humidity may have been found to be significant as a narrow range of internal environmental data was collected. Over the course of the test sessions, the relative humidity varied between 30 and 60%. This is well within the typical 40 - 70% comfort threshold. These theories cannot be corroborated as more detailed weather data (including rainfall), occupancy levels, and objective health measures were not collected. Collecting data over a broader range of environmental conditions with the inclusion of the additional measures mentioned would help to corroborate this finding.

4.5.2.2 Relationships between the Internal Objective Environment Measures

Operative temperature and air temperature ($r_s = 0.89$, $p < 0.01$) had a highly significant and strong, positive relationship. Air temperature ($r_s = 0.18$, $p < 0.05$) and operative temperature ($r_s = 0.21$, $p < 0.01$) were also positively related to lux level, although these relationships were weaker. Increased air and operative temperatures are a result of increased solar radiation and as visible light forms part of the solar radiation spectrum, it is unsurprising that as the lux levels increased, so did the temperature. It is likely that these relationships are weak because the blind position and any cloud cover would have created variations in the lux level data. For example, on Test Day 3, the internal air temperature was measured at 28°C but the internal lux level was < 300 lux. Additionally, if the data was collected in the winter period, we may have found that the temperatures were cooler internally but there may have still been high illuminance levels because of the low angle winter sun (on a clear day). This would have also created variation in the relationship between temperature and illuminance and resulted in a similar weak relationship.

Relative humidity was positively related to CO_2 levels ($r_s = 0.30$, $p < 0.01$) and negatively related to noise ($r_s = -0.27$, $p < 0.01$). Both relationships were weak but highly significant. The positive relationship between CO_2 and relative humidity was most likely caused by the offices being unventilated during the test sessions. If the offices were ventilated or the heating system was active, it is unlikely that this relationship would have been significant (Gładyszewska-Fiedoruk, 2013; Sharpe et al., 2015; WHO, 2009). The negative correlation between dBA and relative humidity suggests that as the humidity increased, the noise levels decreased. Outdoors and in large internal spaces (> 3000 m^3), large increases in humidity (20 - 80%) can increase the Sound Power Level (SPL) by < 5 dB for frequencies between 250 Hz and 4,000 Hz (Gomez-Agustina et al., 2014; Liptai et al., 2015). Increases in humidity are more effective at influencing higher frequencies (> 1000 Hz) than lower frequencies of sound. The effect of small changes in humidity (≤ 20 %) in smaller spaces (< 3000 m^3) as observed in this study[34] has not been well researched as they are considered negligible. It is likely that this relationship was found because of the narrow range in humidity conditions recorded, and potentially because of the other confounding factors that were not recorded. For example, the amount of rainfall would have altered the internal humidity levels.

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[34] Relative humidity varied between 40 and 60% overall. See Table 31, p. 165.

4.5.3 Subsequent effect of variation in the Internal Environment on Subjective Perceptions and Objective Productivity (Objective B)

Hierarchical regressions were produced to identify how the internal objective environment conditions varied and predicted the participants' responses to the questions and performance in the tests (Objective B). Below is an explanation of the outputs of the hierarchical regressions and what steps were followed to ensure the assumptions required to carry out a hierarchical regression were met (Field, 2009). To meet the assumptions, the blind position could not be entered into the regression as an independent variable (IV) as it shared too great a proportion of variance with lux level. In the interpretation of the results, lux level can also be inferred as blind position. Operative temperature and air temperature also shared a large proportion of variance. However, they did not surpass the thresholds for identifying multicollinearity and they were both included in the regressions.

The R^2, the change in R^2 and the Standardised β coefficient (Std. β) are the most useful outcomes of the hierarchical regressions. The significant R^2 and change in R^2 identified how the objective internal environmental variables (IVs), specifically operative and air temperatures, illuminance, relative humidity, noise levels (dBA) and CO_2 levels, varied depending on the participants' subjective responses and their performance in the tests (DVs). The Std. β identifies how the IVs predicted a change in the DVs. It is expected that the IVs entered will not explain all of the variance or be able to predict the participant's responses to the questions and their performance in the tests (DVs). This is because there are other variables that were either un-measured or not included in the regression. For example, it is known that an occupant's sensation of air temperature may alter depending on what clothes the occupant wears, how recently they ate or drank, their activity level (e.g., walking, running, and sitting), and their position in relation to glazed facades (CIBSE, 2015; Nicol et al., 2013). As these variables were not entered into the model, there will be some unaccounted-for variance.

The following sections report a summary of the hierarchical regression models that produced a significant R^2, change in R^2 and Std.β ($p < 0.05$) for each grouping of the measures (e.g., thermal comfort, visual comfort, air quality etc.). A more detailed reporting of all significant hierarchical regression models is provided in Appendix G. The R^2 and change in R^2 values of each regression produced are presented in the form of pie charts. Each pie chart shows which objective internal environment variable (IV) and how much the IVs varied participants' responses and their performance on the tests (DV). The unaccounted-for variance is represented by the 'Non-measured Variable' portion of the pie charts. The 'Remaining Measured Variable' portion relates to the last step of the model where all IVs that were not significantly correlated with the DV were entered into the model. Therefore, the 'Remaining Measured Variables' segment of the pie chart reflects the variation in the participants' responses caused by the changes in multiple IVs that cannot be separated. In addition, a list of the significant Std.βs for each DV has been provided and the IV with the greatest predictive power is identified with an example of how a one standard deviation increase in the IV predicts the outcome of the DV when all other IVs remain constant. This is followed by a discussion of the results in relation to the existing research literature, providing context as to whether the findings have been previously identified in research literature.

Hierarchical Regression Outputs

R^2 - The percentage of variance that the IV (or IVs) contributes to the model. The higher the number, the greater the contribution. Each R^2 value has a significance level which assures us that the variance was not found by chance ($p < 0.05$).

Change in R^2 - Identifies the difference in variance contributed to the DV between the two models. For example, if air temperature was the only IV added in the first model and this model had a R^2 of 0.11, and in the next model operative temperature was added and this model had a R^2 of 0.12, then the change in R^2 would be 0.01. This change in R^2 suggests that the operative temperature explained 1% of the variance in the DV.

The Standardised Coefficient β (Std. β) - Identifies how a one standard deviation (SD) increase in the IV predicted the outcome of the DV in standard deviations when all other variables remain constant. A Std. β is provided for each IV within a model. The higher the integer, the greater the IV is at predicting a change in the DV. The polarity explains the way that it affects the DV (positively or negatively). The unit of the coefficient is in standard deviations so they can be easily compared between the variables and used to identify which IV predicts the most change in the DV. Each coefficient has a significance level ($p < 0.05$) associated with it that identifies whether the Std.β produced arose by chance. The product of the significant Std.β for each IV and the SD of the DV identifies how a one SD increase in the IV would alter the DV as an absolute value. For example, if the Std.β of air temperature was 0.5 and this significantly predicted an increase in thermal sensation (measured on a 5-point scale with a SD of 1.11), then a one standard deviation increase in air temperature (SD = 1.6°C) would result in a 0.55 pt increase in the responses reflecting a warmer thermal sensation (Std.β 0.5 x SD 1.11) (i.e., a 1.6°C increase in air temperature would result in a 0.55 pt warmer thermal sensation response).

Hierarchical Regression Procedure

Multicollinearity Assumptions:

Prior to conducting a hierarchical regression, a multicollinearity check of the IVs was required (Field, 2009). This is because when two IVs are collinear, it is difficult to identify which IV is contributing variance to the DV. Consequently, the researchers are unable to report the variances confidentially and the IVs can be perceived as interchangeable. The Spearman Rho correlation matrix conducted in Section 4.5.2 (p. 183) suggests that multicollinearity could be an issue because two strong significant relationships ($r_s \geq 0.8$, $p < 0.01$) were found between operative temperature and air temperature, and blind position and lux level. All other relationships were weak ($r_s \leq 0.3$) and were less of a concern as a result.

To check for potential collinearity issues, an initial regression including all of the IVs was carried out, and the collinearity statistics and the variance inflation factor (VIF) were used to identify any multicollinearity issues. The collinearity statistic identifies multicollinearity and the VIF quantifies the severity of the collinearity. The collinearity statistic was set at a tolerance level of ≥ 0.20 and a variance inflation factor (VIF) was set at (VIF) ≤ 5 according to Field (2009). The initial regression found that the threshold for collinearity was exceeded when both blind position and lux level were included in the regression. However, it was not exceeded when both operative temperature and air temperature were included within the regression (although they were close to the tolerance levels). Therefore, the blind position IV shared an unacceptable level of variance with the internal lux level IV. One of these variables needed to be excluded from the regressions. The variance between air temperature and operative temperature was considered to be acceptable, therefore both variables were included in the regressions.

The variance shared between the internal lux level and blind position is understandable as when the blinds are retracted, more daylight can enter, thus increasing the internal lux levels. The variance shared by air temperature and operative temperature is also logical as air temperature is considered within the formulae for operative temperature[35] (Fanger PO, 1970; Nicol et al., 2012). The air velocities across the test sessions were very similar (stable and low < 0.01 m/s) (see Section 4.3.4.6.2, p. 158) so we can assume that the relationship between the air temperature and operative temperature was not completely collinear. This is because the internal mean radiant temperature would have altered depending on the

[35] $\Theta = \frac{T_{int}\sqrt{(10\text{ v})}+\text{mrt}}{1+\sqrt{(10\text{ v})}}$ where Θ is operative temperature, T_{int} is internal air temperature (°C), mrt is the mean radiant temperature (°C) and v is air velocity (m/s) (CIBSE, 2015).

blind position, the varying external weather conditions, occupancy, occupancy-related factors (e.g., computers being used), and the differences in the surrounding surface temperatures within the office. Based on the results of the initial regression and the collinearity statistics produced, the decision was made to remove the blind position along with the preceding regressions. In all of the regressions produced, the collinearity statistics were checked to ensure that the operative temperature and air temperature met the collinearity limits. This finding also assisted in the interpretation of the outputs of the regressions as we can assume that within the results of the regression, blind position and lux level are interchangeable. This means that where lux level is significant, it suggests that the blind position will also be significant. Additionally, because the operative temperature and air temperature almost exceeded the collinearity statistic threshold, the variables may also be considered interchangeable.

Order of Entering the Independent Variables (IVs):

A Spearman's Rho correlation was produced between each of the DVs (e.g., question and test response) and all the IVs (e.g., the internal objective environmental variables). The IVs were then entered into the regression at separate steps according to the significance of the relationships defined by the Spearman Rho correlation coefficient. Significant IVs ($p < 0.05$) in the correlation were entered separately and those that were non-significant were grouped and entered in the last step.

4.5.3.1 Subjective Internal Environment

4.5.3.1.1 Thermal Comfort

The participants' responses were significantly varied by all of the internal objective environmental variable (IVs). The amount of variance contributed and the IVs responsible for this variance differed for each question (DV). Figure 66 summarises which IVs contributed and what variation they created within the participants' responses to each thermal comfort measure. This is indicated by the R^2 and the change in R^2 in the hierarchical regressions produced. The internal objective environmental variables (IVs) explained between 9 - 24% of the variation in the participant responses overall, leaving 76 - 80% of the variance unaccounted for.

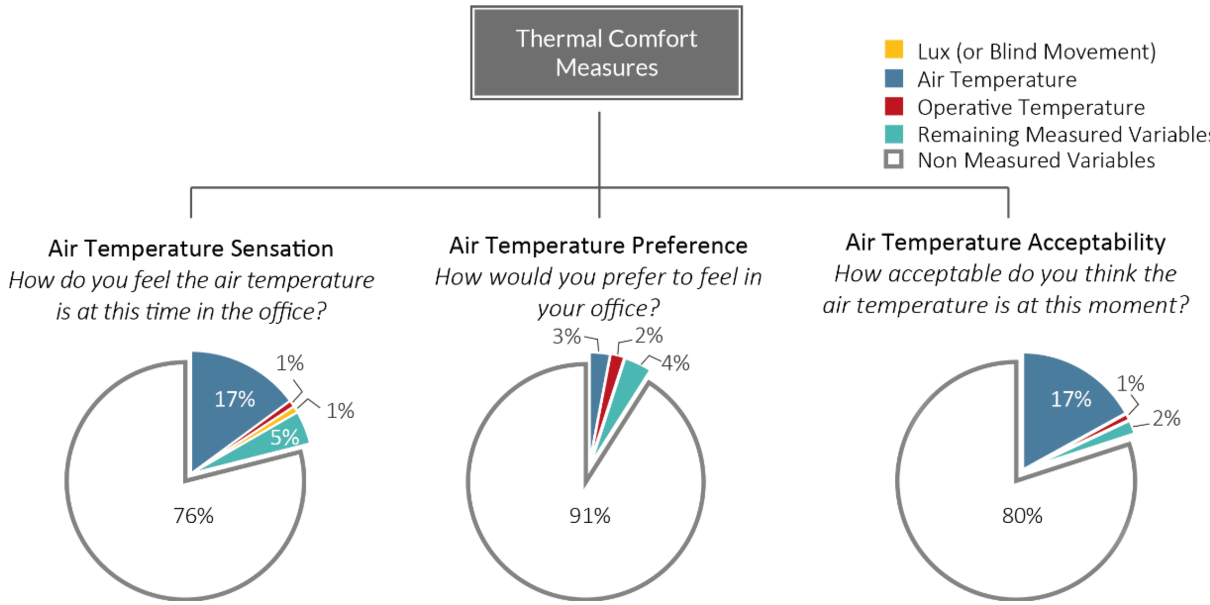

Figure 66. Thermal Comfort Measures and the contributing variances.

In Figure 66, it can be observed that air temperature contributed the largest proportion of variance (3 - 17%). It was also the most frequent singular IV that varied the participants' responses. Air temperature explained 17% of the variance in participants' sensation and acceptability of the air temperature, and 3% of the variance in participants' air temperature preference response. Operative temperature was the second most frequent singular IV to contribute variance and it explained 1 - 2% of the variance in all three measures. Lastly, lux level (or blind movement) contributed 1% to one of the measures and a combination of the remaining IVs contributed between 2 - 5% of the variance.

The significant Std.β coefficients identified that:

- A one standard deviation increase in either air temperature (Std.β = 0.41, SD = 1.6°C), relative humidity (Std.β = 0.19, SD = 5.06%) or dBA (Std.β = 0.16, SD = 1.89 dBA) predicted the participants perceiving warmer air temperatures (SD = 1.11 pts, on a 7-point scale) when all other IVs were held constant. Air temperature had the greatest predictive power (Std.β = 0.41). The results suggest that:
    - A 1.6°C increase in air temperature predicted a 0.46 pt greater perception of warmer air temperatures when all other internal environment conditions remained the same.

- A one standard deviation increase in air temperature (Std.β = -0.18, SD = 1.6°C) predicted the participants preferring cooler air temperatures when all other

IVs were held constant. However, when all variables were included in the model, a one standard deviation increase in CO_2 (Std.β = 0.23, SD = 468 PPM) alone predicted the participants preferring warmer air temperatures (SD = 0.58 pts, on a 3-point scale). CO_2 had the greatest predictive power (Std.β = 0.23). The results suggest that:

- An increase of 468 PPM in CO_2 levels predicted a 0.13 pt greater preference for warmer air temperatures when all other internal environment conditions remained the same.

- A one standard deviation increase in air temperature (Std.β = -0.43, SD = 1.6°C) predicted the participants finding the air temperatures less acceptable (SD = 0.66 pts, on a 3-point scale) when all other IVs were held constant. The results suggest that:
    - A 1.6°C increase in air temperature predicted a 0.28 pt less acceptable perception of air temperature when all other internal environment conditions remained the same.

Interestingly, all of the IVs contributed variance to participant's responses to the thermal comfort measure questions. Some of the IVs are more well known to influence thermal perceptions (e.g., temperature and relative humidity) while the other IVs (lux level, dBA, and CO_2 levels) can only be explained by their interrelationships with the other factors, specifically changes in solar radiation exposure and occupancy. Both of these are known to have an impact on a person's thermoregulatory system which subsequently affect an individual's perception of thermal comfort (CIBSE, 2015; Fang *et al.*, 2004). For example, in Figure 66, it can be observed that lux level varied the participants' perceptions of the air temperature, and increases in illuminance, and internal temperatures are both by-products of increased exposure to solar radiation. The exposure to solar radiation would have varied throughout the test sessions depending on whether the blinds were closed or open and on the level of cloud cover externally. Nevertheless, the lux levels only varied the participants' responses to the question by 1%. This suggests that the position of the blinds and the amount of external cloud cover had little impact on how the participants responded to the thermal comfort questions. Indicating that exposure to solar radiation was not the primary reason why the internal temperatures were perceived as overly warm. This is also supported by the outputs of the Std.β that did not identify lux level as a significant predictor. Most likely this is because when the blinds were closed and the internal conditions were darker, the participants still reported the conditions as being warm. They preferred them to be cooler and felt that the conditions were less acceptable.

The dBA and CO_2 levels also contributed a small amount of variance as part of the 'Remaining Measured Variables'. Both variables are more commonly associated with changes in the number of occupants within a space (i.e., occupancy). Noise and CO_2 levels in unventilated spaces often have a positive relationship with the number of occupants in a space. Increases in occupancy also result in an increase in internal thermal gains from both the participants themselves and the equipment that they use (e.g., computers and lighting) (CIBSE, 2013). It is possible that the perceptions of thermal comfort also varied because of occupancy. Unfortunately, occupancy was not accurately monitored[36] so we are unable to determine whether the changes in dBA and CO_2 are related to the changes in the number of occupants present in the office. However, the significant Std. β values partly support this hypothesis. An increase in dBA predicted that the participants would report a warmer thermal response. However, an increase in CO_2 levels predicted that the participants preferred further warmer temperatures. The Std. β in relation to CO_2 levels conflicts with our hypothesis as we would have expected to find that an increase in CO_2 levels predicted a preference for cooler conditions. On further analysis of the data collected, the author can only infer that CO_2 levels predicted a preference for warmer conditions because of the skewed distribution of the data collected. Only 10 participant responses suggested that they would prefer "Warmer" conditions. When these conditions were reported, the mean CO_2 levels were approximately 300 ppm higher than when "Cooler" conditions were preferred and approximately 250 ppm higher than when a "No Change" response was provided. This highlights a limitation of the study design and the method of analysis. A longer data collection period inclusive of a cooler period would have provided a more normally distributed data set to assess. The sufficient collection of the occupancy data would have been useful in robustly identifying how thermal sensation was varied and predicted by the dBA and CO_2 levels. Nevertheless, the Std.β values appropriately identify air temperature as having the greatest predictive power in two out of the three measures of thermal comfort, and increases in relative humidity predicting a warmer thermal response is also a common finding in prior research literature (Fang et al., 2004; Nicol et al., 2012).

Even though operative temperature contributed variance to all of the thermal comfort questions, it did not significantly predict the participant responses. This occurred because of the collinear relationship found between air temperature and operative temperature. To

[36] The participation of the occupants in the tests identified when and how many participants were taking part but the data collected did not consider monitoring those participants remaining in the office who were not taking part in the tests or other people walking through the offices or talking with the participants in the test offices.

prove that this was the case, the regressions were re-run without air temperature in the model. In all cases where air temperature either contributed variance or significantly predicted the thermal comfort measure, operative temperature replaced air temperature. The amount of variance provided and the predictive power of operative temperature in the new regressions was slightly less than the sum of the variance and the predictive power of air temperature and operative temperature combined.

4.5.3.1.2 Air Quality

Three of the six air quality measures were significantly varied by all of the internal objective environmental variables (IVs). Figure 67 summarises which IVs contributed and what proportion of variation they explained in each measure as indicated by the R^2 and the change in R^2 in the hierarchical regressions produced. The measures that produced a non-significant regression are represented in Figure 67 by a pie chart where 100% of the variance is explained by the 'Non-Measured Variables'. The IVs explained 11 - 20% of the variance in the participant responses overall, leaving 80 - 89% of the variance unaccounted for.

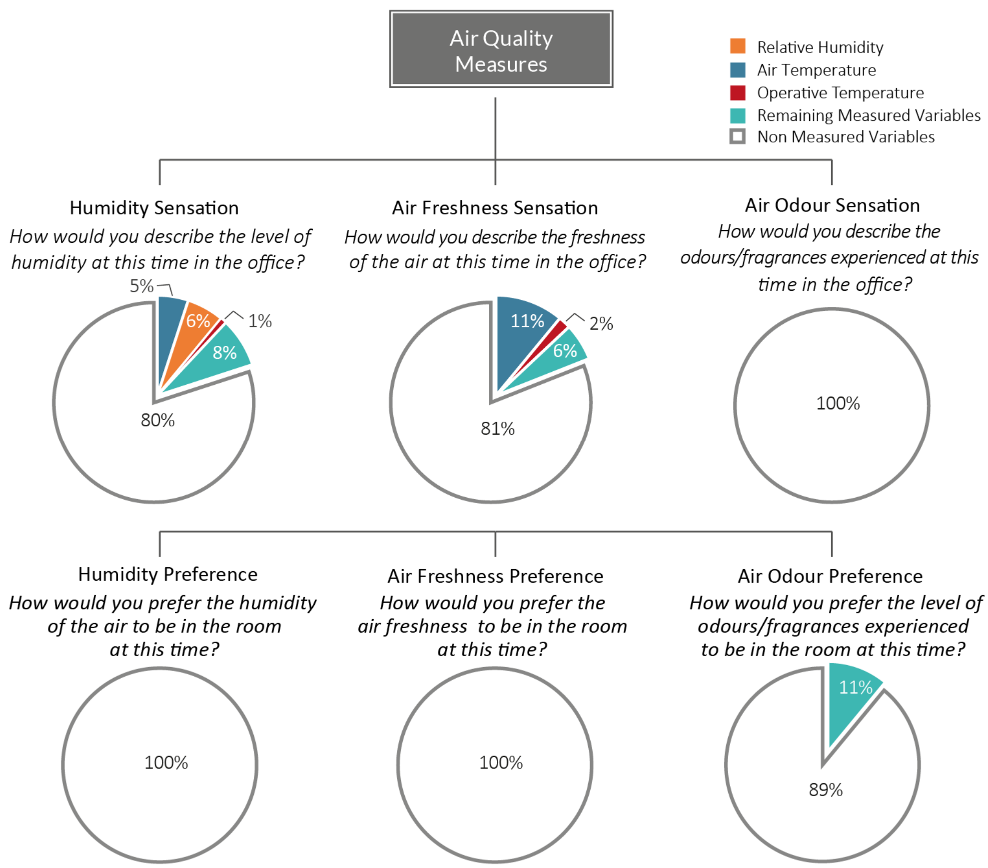

Figure 67. Air Quality Measures and the contributing variances.

Air and operative temperature contributed to two of the three significant air quality measures as singular IVs. Air temperature was the largest singular IV that contributed variance and it explained 5 - 11% of the variance within the humidity and air freshness sensation measures. Operative temperature contributed between 1 - 2% to the same two measures. Relative humidity was the only other singular IV to contribute and it explained the second largest amount of variance (6%) in the humidity sensation measure. A differing combination of IVs made up the 'Remaining Measured Variables' portion of the variance in each of three measures. The 'Remaining Measured Variables' explained 8% of the variance in the humidity sensation measure, 6% of the variance for air freshness sensation, and 11% of the variance in air odour preference. It was the sole contributor of variance in air odour preference, and it contributed the majority of variance to the participants' humidity sensation response.

The significant Std.β coefficients identified that:

- A one standard deviation increase in either air temperature (Std.β = 0.36, SD = 1.6°C) or relative humidity (Std.β = 0.35, SD = 5%) predicted a more humid sensation response (SD = 1.15 pts, on a 7-point scale) when all other IVs were held constant. Additionally, a one standard deviation increase in CO_2 (Std.β = -0.25, SD = 468 PPM) predicted a less humid sensation when all other IVs were held constant. Air temperature (Std.β = 0.36) and relative humidity (Std.β = 0.35) had the greatest (and a very similar) predictive power in the model. For these two IVs, the results suggest that:
    - A 1.6°C increase in air temperature or a 5% increase in relative humidity predicted participants reporting either a 0.42 or a 0.40 pt more humid sensation response, respectively when all other environmental conditions remained the same.

- When only air temperature was included in the model, a one standard deviation increase in air temperature (Std.β = -0.33, SD = 1.6°C) predicted a stuffier air freshness sensation (SD = 1.07 pts, on a 7-point scale) when all other IVs were held constant. However, when all IVs were included in the model, relative humidity was the only significant predictor found (Std.β = -0.24, SD = 5%) and a one standard deviation increase predicted a stuffier air freshness sensation. Air temperature had the greatest predictive power (Std.β = -0.33). The results suggest that:

- A 1.6°C increase in air temperature predicted the participants reporting a 0.35 pt stuffier air freshness sensation response when all other environmental conditions remained the same.

- A one standard deviation increase in either air temperature (Std.β = 0.56, SD = 1.6°C) or relative humidity (Std.β = 0.20, SD = 5%) predicted a preference for more pleasant odours and fragrance (SD = 0.53 pt, on a 3-point scale) when all other IVs were held constant. In the same model, a one standard deviation increase in either CO_2 (Std.β = -0.19, SD = 468 PPM) or operative temperature (Std.β = -0.51, 3.0°C) predicted a preference for less pleasant odours and fragrance preference when all other IVs were held constant. Air temperature (Std.β = 0.56) had the greatest predictive power of the four IVs. The results suggest that:
    - A 1.6°C increase in air temperature predicted the participants reporting a 0.30 pt preference for more pleasant odour and fragrances when all other environmental conditions remained the same.

Increased air temperatures and relative humidity levels are known to negatively affect the perceptions of air quality (Fang et al., 2004; Witterseh et al., 2004). In this study, when air temperature and relative humidity increased, this predicted more negative responses to the air quality measures (i.e., the air was humid, stuffier, and the participants preferred more pleasant odours and fragrances). These results agree with similar research carried out by Witterseh et al. (2004) even though slightly different questions were posed. Witterseh et al. found that at higher temperatures, the air quality was generally perceived as less acceptable, stuffier, and stronger odours were detected. Operative temperature also contributed variance to the air quality measures, most likely because of its collinear relationship with air temperature. However, it may have also varied the perceptions because increases in surface temperature (considered in the calculation of the mean radiant temperature and included in the calculation of operative temperature) can increase the release of volatile organic compounds (VOCs) from surface finishes (e.g., carpet and furniture) (Kang et al., 2010; Kim et al., 2012). VOCs are another measure used to identify internal air quality. This perhaps would have been useful to incorporate within this study to validate this theory.

Generally, CO_2 levels are used more frequently in Post Occupancy Evaluations (POEs) as an indicator of either air quality or ventilation effectiveness (CIBSE, 2020). However, in this study, the CO_2 levels did not vary participants responses as a singular IV. It was not identified as one of the leading predictors of the air quality measure. However, CO_2 levels were identified as a predictor of the air quality measures in the evaluations of the Std.β but had a lower predictive power than air temperature and relative humidity. Unusually, an increase in CO_2 levels predicted that there was a preference for less pleasant odours and fragrances. Considering that high CO_2 levels are associated with poor air quality and an increase in occupancy, it is surprising that a rise in CO_2 levels did not correspond with a preference for more pleasant odours. The offices were un-ventilated (the windows were closed) and the temperatures experienced were generally warm (M = 25.4°C), therefore it is more likely that the presence of more occupants would cause undesirable odours within the office space (e.g., from perspiration). Additionally, operative temperature (Std.β = -0.51, 3.0°C) and air temperature (Std.β = -0.56, 1.6°C) predicted the occupants' responses to the question in opposing ways. An increase in air temperature predicted a preference for more pleasant odours and an increase in operative temperature predicted a preference for less pleasant odours. Potentially, unmonitored factors have contributed to these unusual results. For example, the participant's use of deodorants and fragrances, and the office cleaning regime. Additionally, as the study was carried out during lunchtime, the odours from food being eaten at their desks or in the kitchen (positioned between the two sets of offices) could have created further variations (noise) in the data set.

4.5.3.1.3 Acoustic Comfort

The acoustic comfort measure was significantly varied by air temperature alone. Figure 68 graphically represents these results as indicated by the R^2 and the change in R^2 in the hierarchical regression produced. Air temperature contributed 3% of the variance, leaving 97% of the variance unaccounted for.

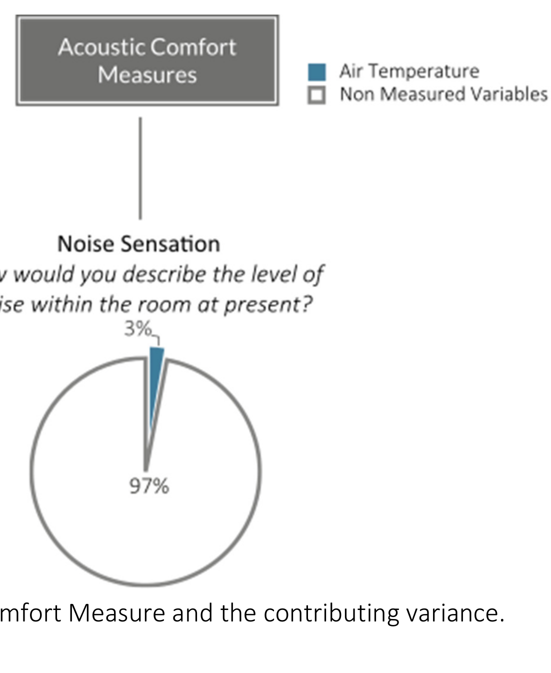

Figure 68. Acoustic Comfort Measure and the contributing variance.

The significant Std.β coefficients identified that:

- A one standard deviation increase in air temperature (Std.β = - 0.18, SD = 1.6°C) predicted a louder noise sensation (SD = 1.44 pt, on a 7-point scale) when all other IVs were held constant. These results suggest that:
    - A 1.6°C increase in air temperature predicted the participants reporting a 0.25 pt noisier acoustic sensation vote when all other internal environment conditions remained the same.

Surprisingly, the metric used to measure noise levels (dBA) did not significantly contribute variance (Figure 68) or predict the participants' responses according to how the participants perceived the level of noise in the office. Instead, a relationship was found between air temperature and the participants' perception of noise. This suggested that an increase in air temperature predicted a noisier perception of sound levels. Even though it was unusual to find this relationship, this can be supported by the research carried out by Guan et al. (2020). Guan et al. identified that when air temperatures increase between 20°C, 25°C, and 30°C and the acoustic conditions remained the same (at either 55 dB, 65 dB, 75 dB, or 85 dB), a group of 18 participants reported feeling more acoustically uncomfortable and more annoyed when exposed to warmer temperatures (i.e., at 25°C and 30°C as opposed to 20°C). However, the work of Witterseh et al., (2004) who tested 30 participants and varied temperatures between 22°C, 26°C, and 30°C, and noise exposures between 35 dBA (representative of a quiet office) and 55 dBA (representative of a loud open-plan office), found that noise acceptability was only significantly affected by changes in the sound levels. Temperature was found to have no effect. The metrics and methods used in these studies differed, so it is difficult to compare the results. However, the results of this study suggest that there is a similar relationship to that identified by Guan et al. (2020). In this study, the air temperatures ranged between the ranges used in both of the previous studies (22°C and 28°C). The acoustic conditions are more comparable to those used by Witterseh et al. (2004) which were significantly lower than those tested by Guan et al. (2020). They ranged between 40 dB and 53 dB across all of the test sessions. The results in this study and the conclusions by Guan et al. suggest that reducing the noise levels could potentially mask the perceived thermal conditions in an office and therefore noise levels should be controlled more stringently in hotter environments. The occupant perceptions of warmer temperatures trigger certain adaptive behaviours to help a person's physiological response in adapting to the warmer conditions. If quieter noise levels can mask the perception of the thermal conditions, this could have a negative impact on a person's objective health e.g., increasing their heat rate, respiratory rate, and dehydration.

4.5.3.1.4 Visual Comfort

Six of the seven visual comfort measures were significantly varied by all of the objective environmental variables (IVs). Figure 67 summarises which IVs contributed and what proportion of variation they explained in each measure as indicated by the R^2 and the change in R^2 in the hierarchical regressions produced. The participants' perception of visual strain produced a non-significant regression model. This is represented in Figure 67 by a pie chart where 100% of the variance is explained by the 'Non-Measured Variables'. The IVs contributed 13 - 40% of the variance overall, leaving 60 - 80% of the variance unaccounted for.

The participants' perception of the level of brightness of the room was varied by lux level and a combination of the remaining IVs by 32% and 8% respectively. Similarly, lux level and the remaining IVs explained the variation in the participants' responses to how acceptable the lighting was and how easy it was to read the questionnaire. Lux level explained 10 and 18% of the variability in these measures and the remaining IVs contributed 8 and 4% respectively. The participants' preference of the lighting conditions was varied by the air temperature (17%), operative temperature (1%), and the remaining IVs which contributed a further 5%. When the participants were asked to identify any glare issues, the CO_2 levels explained 5% of the variance in responses. Lux level contributed a further 4%, while operative temperature and air temperature explained 2% and 1% respectively. Additionally, 1% of the variance was contributed by the remaining measured variables (i.e., dBA and relative humidity). Lastly, participant satisfaction with the view was explained by lux levels (11%), air temperature (9%), CO_2 levels (2%), and operative temperature and the remaining IVs (1%).

Unsurprisingly, lux level was the most frequent and largest singular IV to contribute variance to the measures. Lux level contributed to four of the six significant measures and overall, it explained 10 - 32% of the variance. Air temperature and operative temperature were the second most frequent singular IVs to contribute variance to the measures as they both contributed to three of the six measures. Air and operative temperature are by-products of solar radiation; therefore, it is unsurprising to find that they altered the participants' responses to the visual comfort questions. The opening and closing of the blinds during the test sessions would have altered both the air and operative temperature within the offices. Of the two variables, air temperature contributed a larger proportion of variance to two out of the three measures by 9 - 17%, where operative temperature contributed 1 - 2%. For the identifiable glare issue measure, operative temperature (2%) contributed slightly more than air temperature (1%).

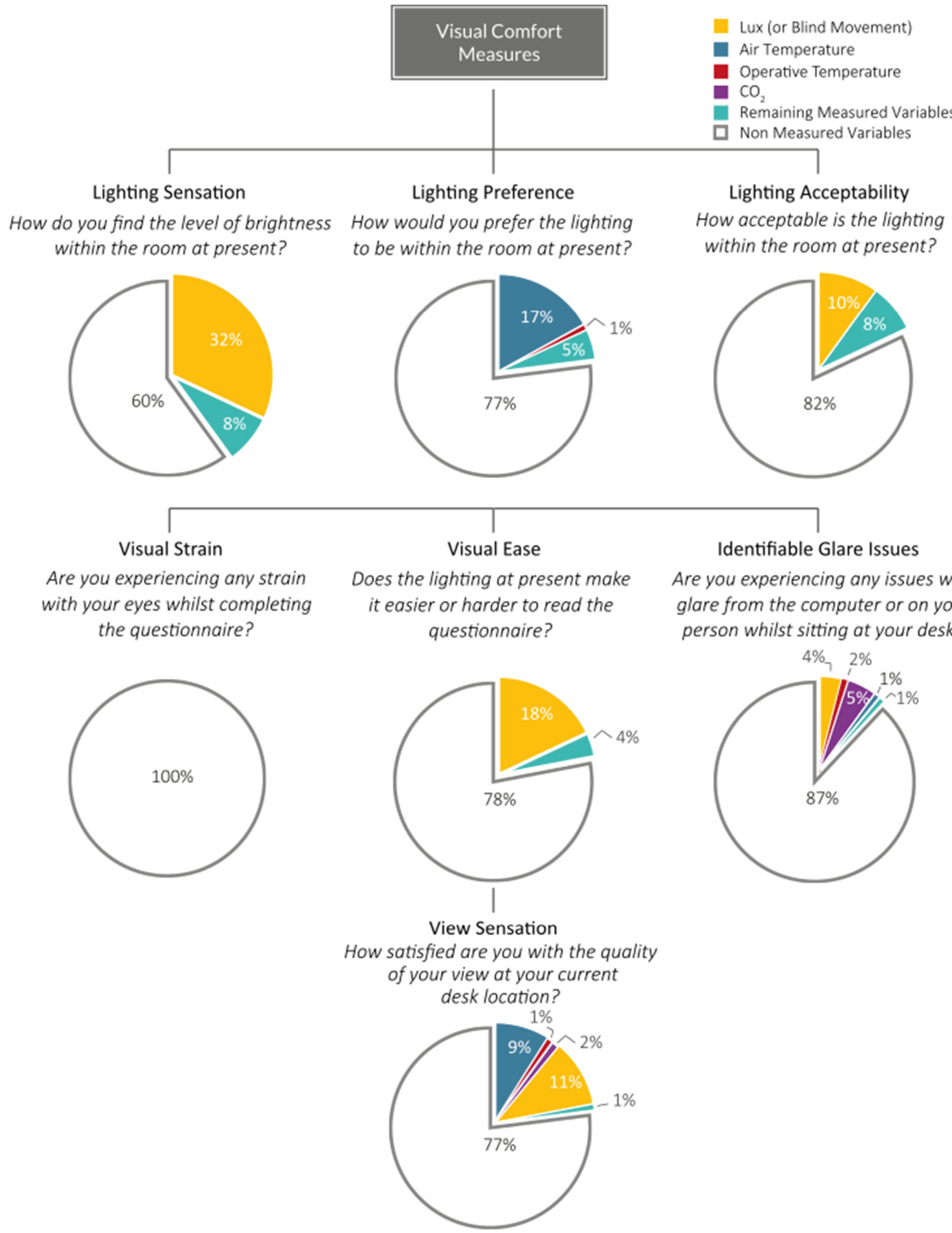

Figure 69. Visual Comfort Measures and the contributing variances.

The significant Std.β coefficients identified that:

- A one standard deviation increase in lux level (Std.β = 0.62, SD = 259 lux) predicted the participants perceiving brighter conditions (SD = 1.30 pts, on a 7-

point scale) when all other IVs were held constant. Additionally, a one standard deviation increase in either operative temperature (Std.β = -0.43, SD = 3.0°C) or CO_2 (Std.β = -0.25, SD = 468 ppm) predicted the participants perceiving darker conditions when all other IVs were held constant. Lux level had the greatest predictive power (Std.β = 0.62). The results suggest that:

  - An increase of 259 lux predicted participants reporting a 0.81 pt brighter visual sensation vote when all other internal environment conditions remained the same.

- A one standard deviation increase in either air temperature (Std.β = 0.35, SD = 1.6°C), relative humidity (Std.β = 0.19, SD = 5%) or dBA (Std.β = 0.16, SD = 1.9 dBA) predicted the participants preferring brighter conditions (SD = 1.11 pts, on a 3-point scale) when all other IVs were held constant. Air temperature had the greatest predictive power (Std.β = 0.35). The results suggest that:
  - A 1.6°C increase in air temperature predicted the participants reporting a preference for 0.39 pt brighter lighting conditions when all other internal environment conditions remained the same.

- A one standard deviation increase in lux level (Std.β = 0.37, SD = 259 lux) predicted the participants reporting that the level of brightness was more acceptable (SD = 0.96 pts, on a 3-point scale) when all other IVs were held constant. The results suggest that:
  - An increase of 259 lux predicted participants reporting a 0.36 pt more acceptable lighting response when all other internal environment conditions remained the same.

- A one standard deviation increase in lux level (Std.β = 0.46, SD = 259 lux) when all other IVs were held constant predicted the participants finding the questionnaire easier to read (SD = 1.11 pts, on a 7-point scale). The results suggest that:
  - An increase of 259 lux predicted participants reporting that it was 0.51 pts easier to read the questionnaire when all other internal environment conditions remained the same.

- A one standard deviation increase in lux level (Std.β = -0.19, SD = 259 lux) predicted the participants reporting less glare issues (SD = 0.64 pts, on a 3-

point scale) when all other IVs were held constant. However, in the final model when all variables were included, a one standard deviation increase in either CO_2 (Std.β = -0.29, SD = 468 ppm) or operative temperature (Std.β = -0.39, SD = 3.0°C) also predicted the participants reporting less glare issues when all other IVs were held constant. Of the three IVs identified, operative temperature had the greatest predictive power (Std.β = -0.39). The results suggest that:

- A 3.0°C increase in operative temperature predicted the participants reporting a 0.25 pt less glare issues when all other internal environment conditions remained the same.

- Five models were produced in the hierarchical regression for view sensation. Air and operative temperature as well as the lux and CO_2 levels were all found to be significant predictors of view sensation in the first four models. In all models, a one standard deviation increase in both air and operative temperature and CO_2 levels predicted a more unsatisfactory view response when all other IVs were held constant. A one standard deviation increase in lux levels predicted a more satisfying view response. However, in the final model when all environmental variables were included in the model, only lux level (Std.β = 0.33, SD = 259 lux) and operative temperature (Std.β = -0.36, SD = 3.0°C) were considered to significantly predict the participant responses to the view sensation question (SD = 1.46 pts, on a 7-point scale) when all other IVs were held constant. Lux level and operative temperature both had similar strengths in terms of predictive power. These results suggest that:
    - A 3.0°C increase in operative temperature predicted the participants reporting a 0.53 pt more unsatisfactory view when all other internal environment conditions remained the same.
    - An increase of 259 lux predicted the participants reporting a 0.48 pt more satisfactory view when all other internal environment conditions remained the same.

Interestingly, the participants' lighting preference was not varied by the lux levels as a singular IV. It was instead varied and predicted by the changes in temperature. The previous literature has identified that even when lux levels are considered comfortable on the work plane (300 - 500 lux) occupants still have a preference for brighter conditions (> 500 lux). This is a common finding within Post Occupancy Evaluations (POEs) as brighter conditions are generally always preferred unless glare is experienced, particularly when it is provided by natural daylight (Alimoglu and Donmez, 2005; Boubekri et al., 2014; Viola et al., 2008). The participants reporting that they still wanted brighter conditions when the illuminance level was already high would have created noise in the dataset and distorted the relationship between the variables, resulting in temperature being a better predictor. The significance of air and operative temperature as a variant in the responses to the visual preference measure can be attributed to the known positive relationship between increases in solar radiation, internal illuminance, and temperature. It is likely that when temperatures were uncomfortably warm, the participants identified that they wanted slightly less bright conditions than when it was cool internally. This is supported by the positive relationship found between lux levels and both operative and air temperature in Section 4.5.2.1 (p. 184). This conflict between internal illuminance and internal temperatures can be observed more clearly in the Std.β results of the participants' perception of view. Both operative temperature (Std.β = -0.36) and illuminance (Std.β = 0.33) were found to be strong predictors of view. However, operative temperature was slightly stronger and predicted the participants perceiving a more unsatisfactory view.

Among the Std.β results, it was also surprising to find that a decrease in lux levels was related to more experiences of glare. Generally, increased illuminance levels are associated with increased experiences of glare, although they can also be caused by uneven distributions of light around the field of view. This relationship is explored further in Section 4.5.4.3.4 (p. 242) where comparisons are made between the participants' responses in closed and open blinds, and Section 4.5.5.2.2 (p. 262) where further analysis is carried out on the interrelationship between the participants' visual perceptions.

Lastly, it was also interesting to find that CO_2 levels varied the participants' responses to the number of identifiable glare issues and the participants' perception of their view. Considering that CO_2 levels are often positively related to occupancy, we can infer that when the occupancy levels were altered, so did people's perception of identifiable glare issues and their satisfaction with the external view. This may be true as the desk layout in the office meant that some of the participants were positioned in front of windows. When seated, they would block the view out of the window and block a proportion of the incoming daylight. Direct sunlight, reflections of sunlight and the window itself were identified as responsible for 38 out of the 130 glare issues (see Figure 55, p. 170). Unfortunately, due to the lack of occupancy data, this hypothesis is unable to be tested further.

4.5.3.1.5 Subjective Comfort and Subjective Productivity

Subjective Comfort

The subjective comfort measure was significantly varied by all of the objective environmental variables (IVs). In line with the previous reporting of the results, Figure 70 graphically represents these results as indicated by the R^2 and the change in R^2 in the hierarchical regression produced. Air temperature explained the most variance (6%), operative temperature contributed 1%, and the remaining measured IVs contributed 3%. This left 90% of the variance unaccounted for.

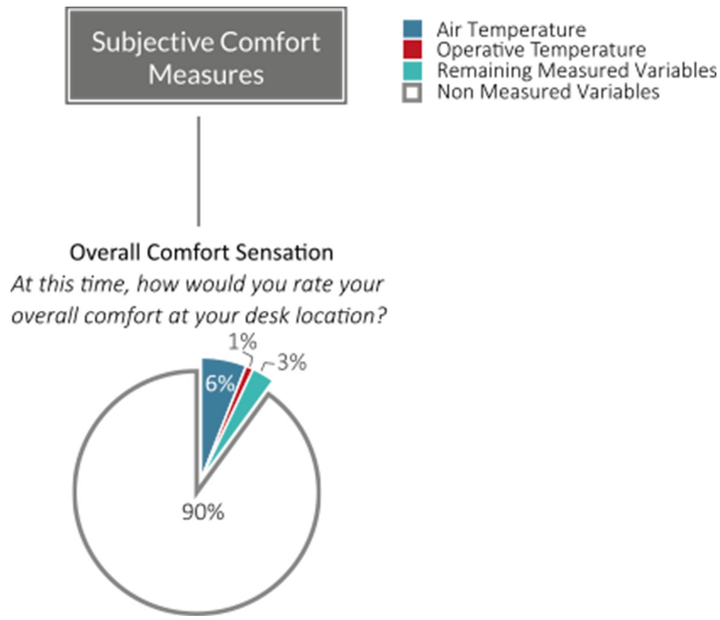

Figure 70. Subjective Comfort Measure and the contributing variances

The significant Std.β coefficient identified that:

- A one standard deviation increase in air temperature (Std.β = -0.28, SD = 1.6°C) predicted the participants responding with a more negative comfort response (SD = 1.44 pts, on a 7-point scale) when all other IVs were held constant. The results suggest that:
  - A 1.6°C increase in air temperature predicted the participants reporting a 0.40 pt more uncomfortable response to the overall comfort sensation vote when all other internal environment conditions remained the same.

The occupant's perception of overall comfort is commonly asked about within Post Occupancy Evaluations (POE) (Nicol et al., 2012). However, in this study, the internal objective environment measures only explained 10% of the variance in the responses. This suggests that a broader range of measures need to be considered in POE evaluations to identify what the leading factors are that influence a person's perception of comfort. The office occupants' perceptions of comfort are affected by a large and exhaustive range of factors other than the internal environment conditions measured and included within this analysis (Clements-Croome, 2018; WGBC, 2014).

The operative temperatures experienced when the participants answered the questions ranged above and within the comfort threshold (22 - 25°C, (CIBSE, 2015)) during the test sessions (25 - 39°C). Therefore, it makes sense that air temperature, which has a collinear relationship with operative temperature, significantly predicted and contributed to the variance in the overall comfort question.

Subjective Productivity

The subjective productivity measures were significantly varied by all of the internal objective environmental variables (IVs). Figure 71 summarises which IVs contributed and what proportion of variation they explained in each measure as indicated by the R^2 and the change in R^2 in the hierarchical regressions produced. The IVs contributed 11 - 23% of the variance overall leaving 77 - 89% of the variance unaccounted for.

It should be noted that one of the measures of subjective productivity was not analysed using hierarchical regression. The measure asked the participants to identify whether there were any external issues that they were aware of affecting their productivity and it was presented as a tick box question with three choices 'Yes', 'No' and 'Maybe'. This did not meet the regression assumptions which require scale data to perform a regression.

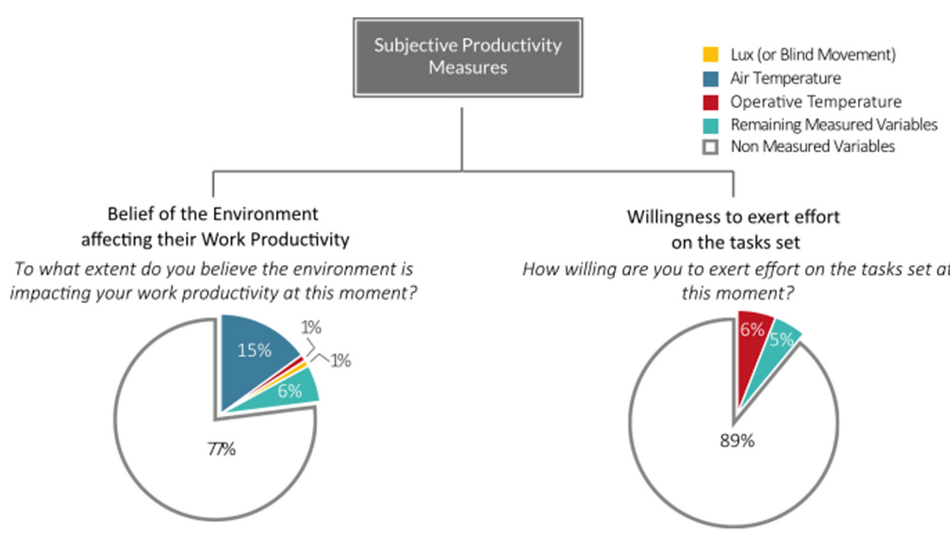

Figure 71. Subjective Productivity Measures and the contributing variances

Operative temperature was the most frequent singular IV across the two measures. It explained 1% of the variance in the question that asked participants' whether they believed the environment was affecting their work productivity and 6% of the variance when they were asked if they were willing to exert effort on the tasks set. However, air temperature contributed the largest proportion of variance (15%) in the belief question. Lux level also explained 1% of the variance of this measure. In both measures, a differing combination of IVs contributed to the 5 - 6% that made up the 'Remaining Measured Variables' proportion of variance.

The significant Std. β coefficients identified that:

- A one standard deviation increase in either air temperature (Std.β = 0.62, SD = 1.6°C) or relative humidity (Std.β = 0.28, SD = 5%) predicted the participants responding with a stronger belief that their productivity was being affected by the surrounding environment (SD = 0.80 pts, on a 4-point scale) when all other IVs were held constant. Air temperature had the greatest predictive power. The results suggest that:
    - A 1.6°C increase in air temperature predicted the participants reporting that their productivity was being more strongly affected by the surrounding environment by 0.40 pt when all other internal environment conditions remained the same.
- A one standard deviation increase in operative temperature (Std.β = -0.44, SD = 3.0°C) predicted a lower willingness to exert effort on the tasks set (SD = 22.77 pts, on a 100-point scale) when all other IVs were held constant. The results suggest that:
    - A 3°C increase in operative temperature predicted the participants reporting that they were 10 pts less willing to exert effort on the tasks set when all other internal environment conditions remained the same.

The overly warm internal conditions influenced how the participants responded to the question that asked whether the participants believed that their environment was affecting their productivity. An increase in temperatures predicted a stronger belief that their productivity was being affected by their surrounding environment. However, the lack of polarity in the question means that we do not know whether they felt like their belief was being positively or negatively affected. Questions need to be posed so the polarity of the question is clear so then the interpretation of the data cannot be questioned. The literature suggests that occupants perform best when they are within a definitive range of air temperatures of 20 - 24°C with an optimum of 22°C (Seppänen et al., 2006). Within this study, the internal temperatures consistently exceeded 22°C[37]. Similarly operative temperatures above 26°C can start to make the participants feel uncomfortable. We can therefore assume that the participants were being affected negatively.

Increases in internal operative temperatures also resulted in the participants suggesting that they felt less willing to exert effort (i.e., less motivated). This finding to some extent agrees with the research undertaken by Lan and Lian, (2009) and Lan et al. (2011) who found that increases in air temperatures resulted in the participants feeling less motivated. However, interestingly in this study, operative temperature was the leading factor. Operative and air temperature in this study were almost collinear with the difference attributed to operative temperature considering variations in mean radiant temperature. This suggests that the combination of both air and mean radiant temperature is a better predictor of a person's motivation. This implies that in offices, people situated next to surfaces that emit radiant heat (e.g., windows, radiators, and in some cases shading products) are more likely to be less motivated when the temperatures increase.

The previous research literature has also identified that exposure to higher illuminance levels positively affects occupants' perceptions of subjective productivity by improving their overall mood and subsequently, their health and well-being (Ticleanu et al., 2015). Therefore, it is interesting that lux levels only varied the participants' belief of their productivity being affected by the surrounding environment by 1 % and that the results did not significantly vary or predict the participants' motivation (i.e., their willingness to exert effort on the tasks). Increases in internal illuminance are a by-product of increased solar radiation exposure. Considering how the position of the blinds varied, the amount of incoming solar radiation subsequently altered the amount of solar thermal gains and daylight entering the space. It is possible the negative effect of the increased temperature due to having the blinds open outweighed the positive effect of the increases in illuminance. It is likely that the results of the hierarchical regressions that assessed the perception of comfort and productivity are only relevant when warmer internal temperatures are experienced. There is the potential that other IVs would have been found to be significant if the temperatures were maintained within comfortable conditions (CIBSE, 2015). For example, increases in internal illuminance may have been identified as a significant predictor if the internal temperatures were lower.

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[37] Air temperatures ranged between 22 - 29°C and the operative temperatures ranged between 25 - 39°C.

4.5.3.2 Health and Well-being

Pre-Test

Four out of the seven health and well-being pre-test measures were significantly varied by all of the internal objective environmental variables (IVs). One of the measures was varied by three of the IVs only. The remaining two measures produced non-significant regression models. Figure 72 summarises which IVs contributed and what proportion of variation they explained in each measure as indicated by the R^2 and the change in R^2 in the hierarchical regressions produced. The measures that produced a non-significant regression are represented in Figure 72 by a pie chart where 100% of the variance is explained by the 'Non-Measured Variables'. The IVs contributed 8 - 14% of the variance, overall leaving 86 - 92% of the variance unaccounted for.

Figure 72. Health and Well-being Measures (pre-test) and the contributing variances

Operative temperature contributed variance to all the significant measures, and it was also the largest singular IV to contribute variance. Operative temperature provided between 3 - 6% of the variance across the significant measures. Air temperature was the second most frequent contributor providing variance to three of the six measures, although air temperature only provided 1% of the variance to the three measures. CO_2 provided a greater amount of variance (3 - 4%) but to the least number of measures (two of the six). In four out of the six measures, a differing combination of IVs contributed to the 2 - 9% that made up the 'Remaining Measured Variables' proportion of variance.

The significant Std. β coefficients identified that:

- A one standard deviation increase in operative temperature (Std.β = 0.48, SD = 3°C) predicted the participants feeling tenser (SD = 0.93 pts, 5-point scale) when all other IVs were held constant. Additionally, a one standard deviation increase in lux level (Std.β = -0.22, SD = 259 lux) predicted the participants feeling less tense when all other IVs were held constant. Operative temperature had the greatest predictive power (Std.β = 0.48), and the results suggest that:
    - A 3°C increase in operative temperature predicted the participants reporting a 0.45 pt tenser response when all other internal environment conditions remained the same.

- A one standard deviation increase in operative temperature (Std.β = 0.21, SD = 3°C) predicted the participants feeling sadder (SD = 0.78 pts, 5-point scale) when all other IVs were held constant. However, when operative temperature, air temperature and CO_2 were included in the model, a one standard deviation increase in CO_2 alone (Std.β = 0.20, SD = 468 ppm) predicted the same response. CO_2 and operative temperature had a similar predictive power in the two models. The results suggest that:
    - A 3°C increase in operative temperature or a 468 ppm increase in CO_2 levels predicted the participants reporting either a 0.15 or 0.16 pt sadder response respectively when all other internal environment conditions remained the same.

- A one standard deviation increase in operative temperature (Std.β = 0.17, SD = 3°C) predicted the participants feeling more anxious (SD = 0.85 pts, 5-point scale) when all other IVs were held constant. The results suggest that:

- A 3°C increase in operative temperature predicted the participants reporting a 0.14 pt more anxious response when all other internal environment conditions remained the same.

- A one standard deviation increase in operative temperature (Std.β = 0.25, SD = 3°C) predicted the participants feeling more confused (SD = 0.78 pts, 5-point scale) when all other IVs were held constant. However, when CO_2 was additionally included in the model, an increase in CO_2 (Std.β = 0.18, SD = 468 ppm) predicted the participants feeling more confused. Operative temperature had the greatest predictive power in the models produced and the results suggest that:
  - A 3°C increase in operative temperature predicted the participants reporting a 0.20 pt more confused response when all other internal environment conditions remained the same.

- In the final model with all IVs included, a one standard deviation increase in either lux levels (Std.β = 0.21, SD = 259 lux) predicted the participants feeling more alert (SD = 1.18 pts, 7-point scale). A one standard deviation increase in operative temperature (Std.β = -0.37, SD = 3°C) predicted the participants feeling less alert. Of the predictors, operative temperature had the greatest predictive power (Std.β = -0.37) and the results suggest that:
  - A 3°C increase in operative temperature predicted the participants reporting a 0.44 pt less alert response when all other internal environment conditions remained the same.

Post-test

Thirteen of the 30 health and well-being post-test measures were significantly varied by all of the internal objective environmental variables (IVs). Five measures were varied by either the operative temperature or air temperature or by both IVs. The remaining 12 measures produced non-significant regression models. Figure 73 and Figure 74 summarise which IVs contributed and what proportion of variation they explained in each measure, as indicated by the R^2 and the change in R^2 in the hierarchical regressions produced. The measures that produced a non-significant regression are represented in Figure 72 by a pie chart where 100% of the variance is explained by the 'Non-Measured Variables'. The IVs contributed 4 - 23% of the variance overall leaving 96 - 77% of the variance unaccounted for.

Figure 73. Health and Well-being Measures (post-test) and the contributing variances (1 of 2)

Figure 74. Health and Well-being Measures (post-test) and the contributing variances (2 of 2)

Like the pre-test questions, operative temperature was the most frequent and largest provider of variance as a singular IV. Operative temperature explained 1 - 12 % of the variance in 16 of the 18 significant measures. Air temperature was the second most frequent singular IV, providing 1 - 6% of variance to 14 of the 18 measures. CO_2 and dBA both contributed to two of the measures providing between 4 - 6% and 2 - 4% of variance, respectively. In 13 of the 18 measures, a differing combination of IVs contributed to the 2 - 11% that made up the ‘Remaining Measured Variables’ proportion of variance.

The significant Std.β coefficients identified that:

- A one standard deviation increase in air temperature (Std.β = -0.21, SD = 1.6°C) predicted the participants perceiving that their lips were drier (SD = 25.89 pts, on a 100-point scale) when all other IVs were held constant. The results suggest:
    - A 1.6°C increase in air temperature predicted the participants reporting that their lips were 5 pts drier when all other environmental conditions remained the same.

- A one standard deviation increase in air temperature (Std.β = 0.16, SD = 1.6°C) predicted the participants perceiving that their skin felt moister (SD = 25.89 pts, on a 100-point scale) when all other IVs were held constant. However, when all variables were included in the model, a one standard deviation increase in operative temperature (Std.β = 0.45, SD = 3°C) alone predicted the participants perceiving that their skin felt moister. Operative temperature had the greatest predictive power (Std.β = 0.45). This result suggests that:
    - A 3°C increase in operative temperature predicted the participants reporting that their skin was 12 pts moister when all other environmental conditions remained the same.

- A one standard deviation increase in air temperature (Std.β = 0.32, SD = 1.6°C) predicted the participants perceiving that their eyes were hurting/smarting less (SD = 26.87 pts, on a 100-point scale) when all other IVs were held constant. A one standard deviation increase in operative temperature (Std.β = -0.50, SD = 3°C) predicted the participants perceiving that their eyes were hurting/smarting more. Operative temperature had the greatest predictive power (Std.β = -0.50). This result suggests that:
    - A 3°C increase in operative temperature predicted the participants reporting that their eyes were hurting/smarting 13 pts more when all other environmental conditions remained the same.

- A one standard deviation increase in operative temperature (Std.β = -0.24, SD = 3°C) predicted the participants experiencing more headache symptoms (SD = 29.04 pts, on a 100-point scale) when all other IVs were held constant. This result suggests that:

- A 3°C increase in operative temperature predicted the participants reporting more headaches by 7 pts when all other environmental conditions remained the same.

- A one standard deviation increase in operative temperature (Std.β = 0.54, SD = 3°C) predicted the participants reporting that it was harder to think (SD = 23.97 pts, on a 100-point scale) when all other IVs were held constant. This result suggests that:
  - A 3°C increase in operative temperature predicted the participants reporting that it was harder to think by 13 pts when all other environmental conditions remained the same.

- A one standard deviation increase in operative temperature (Std.β = 0.22, SD = 3°C) predicted the participants feeling dizzier (SD = 26.31 pts, on a 100-point scale) when all other IVs were held constant. This result suggests that:
  - A 3°C increase in operative temperature predicted the participants reporting they felt dizzier by 6 pts when all other environmental conditions remained the same.

- A one standard deviation increase in operative temperature (Std.β = -0.23, SD = 3°C) predicted the participants feeling bad (SD = 24.00 pts, on a 100-point scale) when all other IVs were held constant. This result suggests that:
  - A 3°C increase in operative temperature predicted the participants reporting they felt 6 pts worse when all other environmental conditions remained the same.

- A one standard deviation increase in operative temperature (Std.β = -0.21, SD = 3°C) predicted the participants finding it more difficult to concentrate (SD = 21.11 pts, on a 100-point scale) when all other IVs were held constant. This result suggests that:
  - A 3°C increase in operative temperature predicted the participants reporting that they found it more difficult to concentrate by 4 pts when all other environmental conditions remained the same.

- A one standard deviation increase in operative temperature (Std.β = -0.18, SD = 3°C) predicted the participants feeling more depressed (SD = 23.67 pts, on a 100-point scale) when all other IVs were held constant. This result suggests that:
    - A 3°C increase in operative temperature predicted the participants reporting that they were 4 pts more depressed when all other environmental conditions remained the same.

- In the first model, a one standard deviation increase in operative temperature (Std.β = 0.25, SD = 3°C) predicted the participants feeling sleepier (SD = 21.02 pts, on a 100-point scale). However, when all variables were included in the model, a one standard deviation increase in the lux levels (Std.β = -0.18, SD = 259 lux). This alone resulted in the participants feeling more alert when all other IVs were held constant. Operative temperature had the greatest predictive power (Std.β = 0.25). This result suggests that:
    - A 3°C increase in operative temperature predicted the participants reporting that they were 5 pts sleepier when all other environmental conditions remained the same.

- A one standard deviation increase in air temperature (Std.β = 0.25, SD = 1.6°C) predicted the participants feeling that the tests were more mentally demanding (SD = 20.85 pts, on a 100-point scale) when all other IVs were held constant. This result suggests that:
    - A 1.6°C increase in air temperature predicted the participants reporting that the tests were 5 pts more mentally demanding when all other environmental conditions remained the same.

- A one standard deviation increase in either CO_2 (Std.β = 0.20, SD = 468 ppm) or air temperature (Std.β = 0.18, SD = 1.6°C) predicted the participants feeling that the tests were more physical demanding (SD = 20.67 pts, on a 100-point scale) when all other IVs were held constant. However, when operative temperature was included in the model (with air temperature and CO_2), an increase in CO_2 levels alone (Std.β = 0.20, SD = 468 ppm) was found to be the only significant predictor. Air temperature and CO_2 levels had similar predictive powers in the models. For these two IVs, the results suggest that:

- A 1.6°C increase in air temperature or a 468 ppm increase in CO_2 level predicted the participants reporting the tests were 4 pts more physically demanding when all other environmental conditions remained the same.

- A one standard deviation increase in air temperature (Std.β = 0.37, SD = 1.6°C) predicted the participants feeling that they had to work harder on the tasks set to achieve their level of performance (SD = 19.67 pts, on a 100-point scale) when all other IVs were held constant. This result suggests that:
  - A 1.6°C increase in air temperature predicted the participants reporting that they had to work 7 pts harder to achieve the same level of performance when all other environmental conditions remained the same.

- A one standard deviation increase in operative temperature (Std.β = 0.57, SD = 3°C) predicted the participants feeling more insecure when completing the tasks (SD = 25.79 pts, on a 100-point scale) when all other IVs were held constant. Both a one standard deviation increase in air temperature (Std.β = -0.32, SD = 1.6°C), dBA (Std.β = -0.22, SD = 2 dBA) and relative humidity (Std.β = -0.25, SD = 5%) predicted the participants feeling less insecure when completing the tasks when all other IVs were held constant. Operative temperature had the greatest predictive power (Std.β = 0.57), and this result suggests that:
  - A 3.0°C increase in operative temperature predicted the participants reporting that they felt 15 pts more insecure when completing the tasks when all other environmental conditions remained the same.

- A one standard deviation increase in either operative temperature (Std.β = 0.39, SD = 3°C) or CO_2 (Std.β = 0.22, SD = 468 ppm) predicted the participants feeling discouraged when completing the tasks (SD = 25.53 pts, on a 100-point scale) when all other IVs were held constant. Operative temperature had the greatest predictive power (Std.β = 0.39). This result suggests that:
  - A 3.0°C increase in operative temperature predicted the participants reporting that they felt 10 pts more discouraged when completing the tasks when all other environmental conditions remained the same.

- A one standard deviation increase in either operative temperature (Std.β = 0.59, SD = 3°C) or CO_2 (Std.β = 0.21, SD = 468 ppm) predicted the participants feeling more irritated when completing the tasks (SD = 28.79 pts, on a 100-point scale) when all other IVs were held constant. Additionally, a one standard deviation increase in lux levels (Std.β = -0.23, SD = 259 lux) predicted the participants feeling less irritated by the tasks when all other IVs were held constant. Operative temperature had the greatest predictive power (Std.β = 0.59). This result suggests that:
    - A 3.0°C increase in operative temperature predicted the participants reporting that they felt 17 pts more irritated when completing the tasks when all other environmental conditions remained the same.

- A one standard deviation increase in operative temperature (Std.β = 0.58, SD = 3°C) and CO_2 (β = 0.27, SD = 468 ppm) predicted the participants feeling more stressed (SD = 27.29 pts, on a 100-point scale) when all other IVs were held constant. Additionally, a one standard deviation increase in relative humidity (Std.β = -0.21, SD = 5%) predicted the participants feeling more stressed when all other IVs were held constant. Operative temperature had the greatest predictive power (Std.β = 0.58). This result suggests that:
    - A 3.0°C increase in operative temperature predicted the participants reporting that they felt 16 pts more stressed when completing the tasks when all other environmental conditions remained the same.

- A one standard deviation increase in operative temperature (Std.β = 0.64, SD = 3°C) predicted that the participants feeling more annoyed (SD = 28.67 pts, on a 100-point scale) when all other IVs were held constant. Additionally, a one standard deviation increase in lux levels (Std.β = -0.25, SD = 259 lux) predicted the participants feeling less annoyed when all other IVs held constant. Operative temperature had the greatest predictive power (Std.β = 0.64). This result suggests that:
    - A 3.0°C increase in operative temperature predicted the participants reporting that they felt 18 pts more annoyed when completing the tasks when all other environmental conditions remained the same.

The internal environment measures explained 4 - 20% of the variation in the participant's responses suggesting that the internal environment conditions measured were not the only factors affecting the participant's perceptions of their health and well-being (Clements-Croome, 2018; WGBC, 2014). Nevertheless, overall operative temperature was the most frequent variable that affected the participants' perception of their health and well-being both pre- and post-test.

The Std.β of the health and well-being measures identified that an increase in temperature (air or operative), CO_2 levels and relative humidity resulted in the participants reporting more negative health and well-being symptoms and that an increase in lux levels resulted in the participants reporting more positive symptoms. Only in one measure did an increase in air temperature, dBA and relative humidity predict a more positive symptom. This was related to the participants feeling less insecure and in another measure, the participant's perception of how dry or moist their skin was meant that both polarities of the scale can be considered a negative symptom. When reviewing which variables had the greatest predictive power in the regressions, both temperature (air and operative) and CO_2 level were the greatest predictors in all of the health and well-being measures and increases were associated with negative symptoms.

In the research literature that has investigated the effects of the internal environmental conditions on health and well-being (Allen et al., 2016; Boyce, 2014; Elzeyadi, 2011; Fang et al., 2004; Lan et al., 2009; Macnaughton et al., 2017; MacNaughton et al., 2016; Wargocki, 1999; Wargocki et al., 2004; WGBC, 2014), operative temperature is not frequently measured as air temperature is often used as a proxy for determining occupant thermal comfort. Overall, this research suggests that higher air temperatures increase the reporting of negative symptoms associated with sick building syndrome. This negatively affects the occupants' mood and motivation to carry out the tasks given in these studies (Fang et al., 2004; Lan et al., 2011; Wargocki et al., 2006).

Lan et al. (2011) previously assessed how tense, depressed, angry, enthused, fatigued, and confused participants were to determine how differing temperatures affect participants' mood. In the study temperatures varied between relatively comfortable temperatures at 22°C and overly warm temperatures at 30°C. These mood-related questions were asked in the two conditions after 20 minutes, 120 minutes, and 250 minutes. After 20 minutes, the participants reported feeling significantly more confused in the warmer temperature condition. After 120 minutes, the participants identified feeling significantly more depressed (sad), angry, less enthusiastic, and fatigued at 30°C. Interestingly, after 120 minutes, there were fewer significant differences, suggesting that the participants' thermoregulatory systems started to adapt to the hotter temperatures. In this study, the questions were given at the very start of the test (2 - 3 minutes after the test had started) and increases in temperature significantly predicted the participants feeling tenser, more sad, more anxious and confused, suggesting that the results of this study generally agree with the results of Lan et al. (2011). The impact of exposure time in this study was not assessed, thus we cannot identify whether the participants eventually adapted to the temperatures and recovered from their initial negative mood responses. Fang et al. (2004) found that increases in both air temperature and relative humidity from 20°C / 40% RH to 26°C / 60% RH significantly increased the number of participants experiencing headaches and participants finding it harder to think. The participants also reported feeling more tired when the air temperatures varied between 20°C / 40% RH to 23°C / 50% RH. Lan et al. (2011) also used the SBS survey and tested the occupants at air temperatures of 22°C and 30°C. At the higher temperatures, the occupants reported feeling like they were unable to work, and they were also finding it harder to think and concentrate. They also felt more depressed and tired, generally reported feeling bad, and had a drier mouth and throat. This study also found that these symptoms were affected by the variations in temperature and similar relationships were found (i.e., an increase in temperature resulted in a more negative association/symptom). The only differentiation was that mouth dryness was not significantly affected by any of the internal environment measures, and that throat dryness and the ability to work were not included in this study. This study also found some additional results which suggest that an increase in temperature results in participants reporting that their lips felt drier, their skin felt moister, and feelings of dizziness.

Lan et al. (2011) also investigated the effects of temperature on the participants' responses to the workload questionnaire. This study's responses found that increases in temperature meant that the participants perceived the tasks as more mentally and physically demanding. This is in agreement with the work of Lan et al. (2011). However, the results differed between the two studies as Lan et al., also found that the participants felt they were more successful at completing the tasks in higher temperatures (30°C) whereas in this study, no significant regression was produced. Increases in temperature were related to the tasks requiring more effort to complete them which was non-significant in Lan et al.'s study. Nevertheless, two out of the three measures agreed with the work carried out by Lan et al. (2011).

As previously mentioned in this analysis, operative temperature and air temperature share variance and they are somewhat collinear because air temperature is considered in the calculation of operative temperature. However, the implication that operative temperature is the leading predictor suggests that variations in the mean radiant temperature (as the air velocities remained consistent throughout the test sessions) contributed to more negative symptoms of health and well-being. Mean radiant temperatures likely varied depending on the position of the blind and the other factors related to occupancy (e.g., people themselves emit radiant heat as does the equipment that they use).

Air temperature, CO_2 level, and dBA also varied the participants' responses to the health and well-being measures as singular IVs. Interestingly, lux level did not significantly vary the participant's response of any of the measures as a singular IV, although it did significantly predict participants responses to the questions. However, it was not considered the strongest predictor of responses in any of the measures. This was surprising as lux level is often identified as a key variable that can influence an occupant's health and well-being within research literature. Ticleanu et al., (2015) reviewed the impact of daylight on health and well-being and cited that mood, alertness, and symptoms of fatigue improve with increased access to daylight. During this study, the participants were exposed to a wide range of internal illuminance levels because of the intervention of opening and closing the blinds. However, the exposure to higher illuminance levels was a result of the increased exposure to solar radiation which subsequently increased the internal temperatures. This relationship is evidenced by the results of the Std.β. Increases in the operative temperature and lux levels conflicted with the responses of the participants with increases in operative temperature predicting negative symptoms of health and well-being and increases in lux levels predicting more positive symptoms. However, where these conflicting predictors were found, the negative impact of increases in operative temperature had a stronger predictive power. This occurred in the measures where participants were asked how tense, alert, annoyed and irritated they were.

Interestingly, for two of the symptoms, operative and air temperature predicted opposing outcomes. This is interesting because air temperature and operative temperature have a positive ($r_s = 0.89$, $p < 0.01$) and relatively collinear relationship. Often, only air temperatures are monitored in studies that assess the impact of the internal environment on the health and well-being of occupants. Increases in operative temperature predicted the participants feeling more insecure and were related to participants reporting that their eyes were hurting/smarting more. Controversially, increases in air temperature predicted participants feeling less insecure and that their eyes were hurting/smarting less. In both cases, operative temperature was the strongest predictor. Considering that the windows were closed and there was little variation in air velocity, this suggests that the increases in mean radiant temperature predicted that the participants would report more negative symptoms. This outweighed the positive symptoms associated with the increases in air temperature. Generally, increases in air temperature are associated with negative health and well-being symptoms, therefore the results here contradict the results of previous research.

The CO_2 levels varied participants' perceptions and predicted the participants feeling sadder and more confused (Figure 72). This included finding the tasks more physically demanding and feeling more discouraged when completing the tasks (Figure 74). However, in three out of the four symptoms, operative temperature had a greater predictive power (i.e., it was better at predicting the participant responses). The participants' perception of how physically demanding the tasks were was predicted almost equally by the increases in air temperature (Std.β = 0.18) and CO_2 level (Std.β = 0.20). Increases in CO_2 affecting the participants' physical perception can be logically explained by the physiological factors (e.g., people need more oxygen to carry out physical activities), although it was surprising to find this outcome as the physical activity required to complete the tasks was minimal. The other symptoms related to increases in CO_2 level are more challenging to explain. The previously discussed interrelation between CO_2 level and occupancy suggests that when the offices had more occupants in the space, it negatively affected the participants' mood. Alternatively, it may be an indicator that changes in CO_2 directly influenced the participant's perception of health and well-being. In previous research, changes in CO_2 levels have not been robustly proven to impact a person's perception or objective health and well-being (CIBSE, 2020). This has been identified as an emerging field of research by CIBSE (2020) that needs further investigation because of the recent research that identified that CO_2 levels directly affect occupants' cognitive function ability. This was in a study carried out by Harvard University where differing concentrations of CO_2 were injected into the air supply (Allen et al., 2016). The lack of data relating to occupancy levels in this study means that we could not confirm that the increases in CO_2 were the cause of poorer health and well-being symptoms.

The finding that increasing dBA levels predicted a feeling of insecurity is unsupported within the extensive literature review carried out by Stansfeld and Matheson (2003). However, it is acknowledged that noise is a subjective variable that can influence occupants differently, depending on the duration and type of noise experienced.

It should be emphasised that the results here are specifically related to the range of internal environmental conditions experienced. If the operative temperatures were within the comfort range, then it is likely that fewer negative symptoms would have been identified. If the temperatures experienced were below the comfort threshold, then differing negative symptoms may have been found significant (e.g., nose running). Similarly, if the other internal environment conditions were altered, there may have been differing overriding factors that contributed variance. For example, if the temperatures were considered comfortable and the noise levels varied widely between very quiet (< 30 dBA) and very noisy (> 60 dBA), then noise may have been considered an overriding factor in the way that the participants perceived certain symptoms (e.g., headaches, fatigue, and the ability to concentrate).

4.5.3.3 Objective Productivity

Work Type Tests

Only one of the seven work type measures of objective productivity produced a significant hierarchical regression result. The number of words typed per minute (WPM) was significantly varied by all the internal objective environmental variables (IVs). Figure 75 shows that operative temperature (7%), CO_2 level (2%), and air temperature (1%) varied the participant responses as singular IVs. The remaining IVs (lux level, dBA, and relative humidity) contributed an additional 3% of the variance. The remaining six measures produced non-significant regression models and are represented in Figure 75 by a pie chart where 100% of the variance is explained by the 'Non-Measured Variables'. The non-significance of these regressions suggests that the IVs considered did not significantly vary the participants' performance in terms of their work productivity.

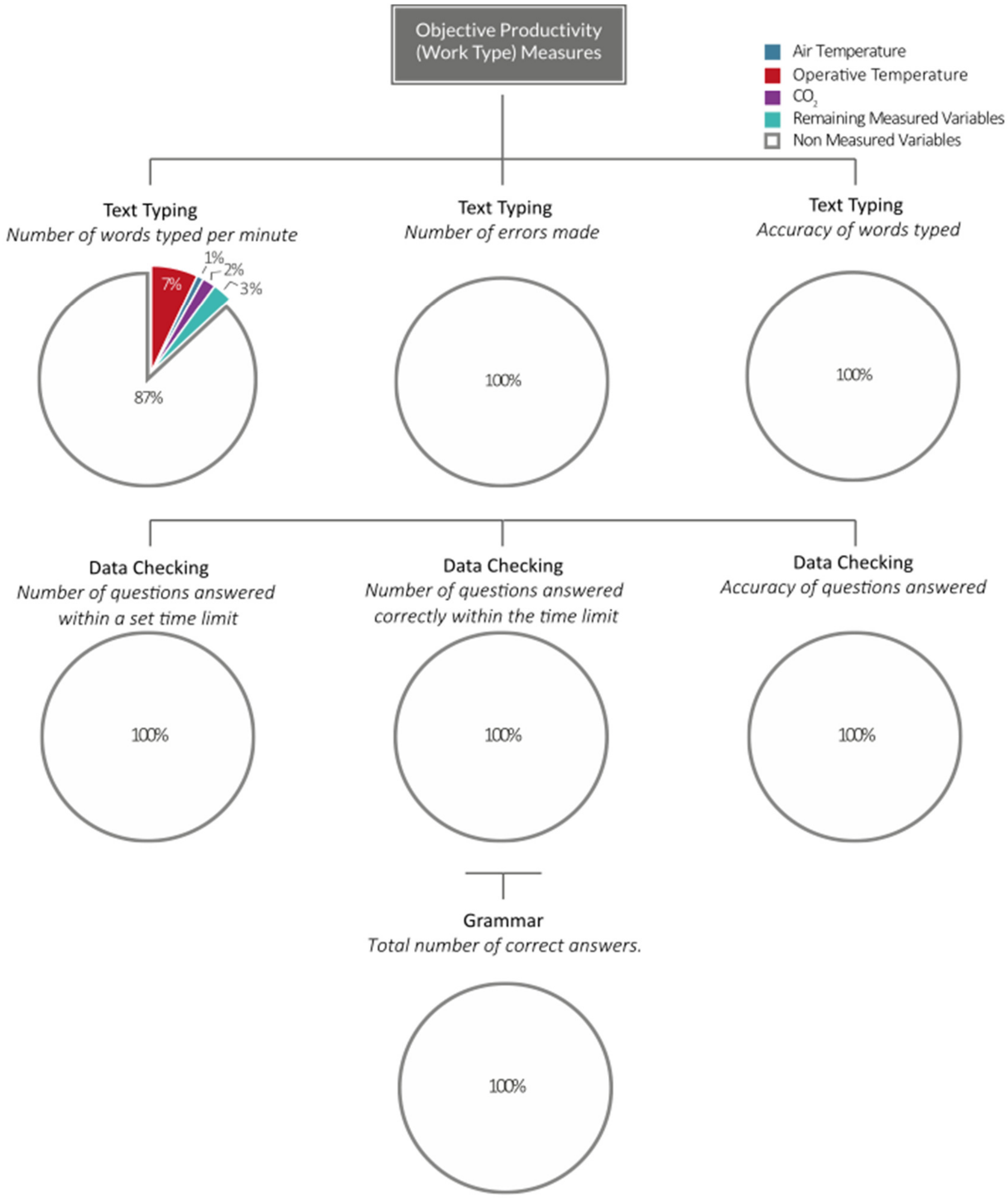

Figure 75. Objective Productivity Measures and the contributing variances

The significant standardised β coefficients identified that:

- A one standard deviation increase in operative temperature (Std.β = -0.27, SD = 3°C) predicted the participants typing fewer words per minute (SD = 12 WPM) when all other IVs were held constant.
    - A 3.0°C increase in operative temperature predicted the participants typing 3 fewer WPM when all other environmental conditions remained the same.

Cognitive Function Tests

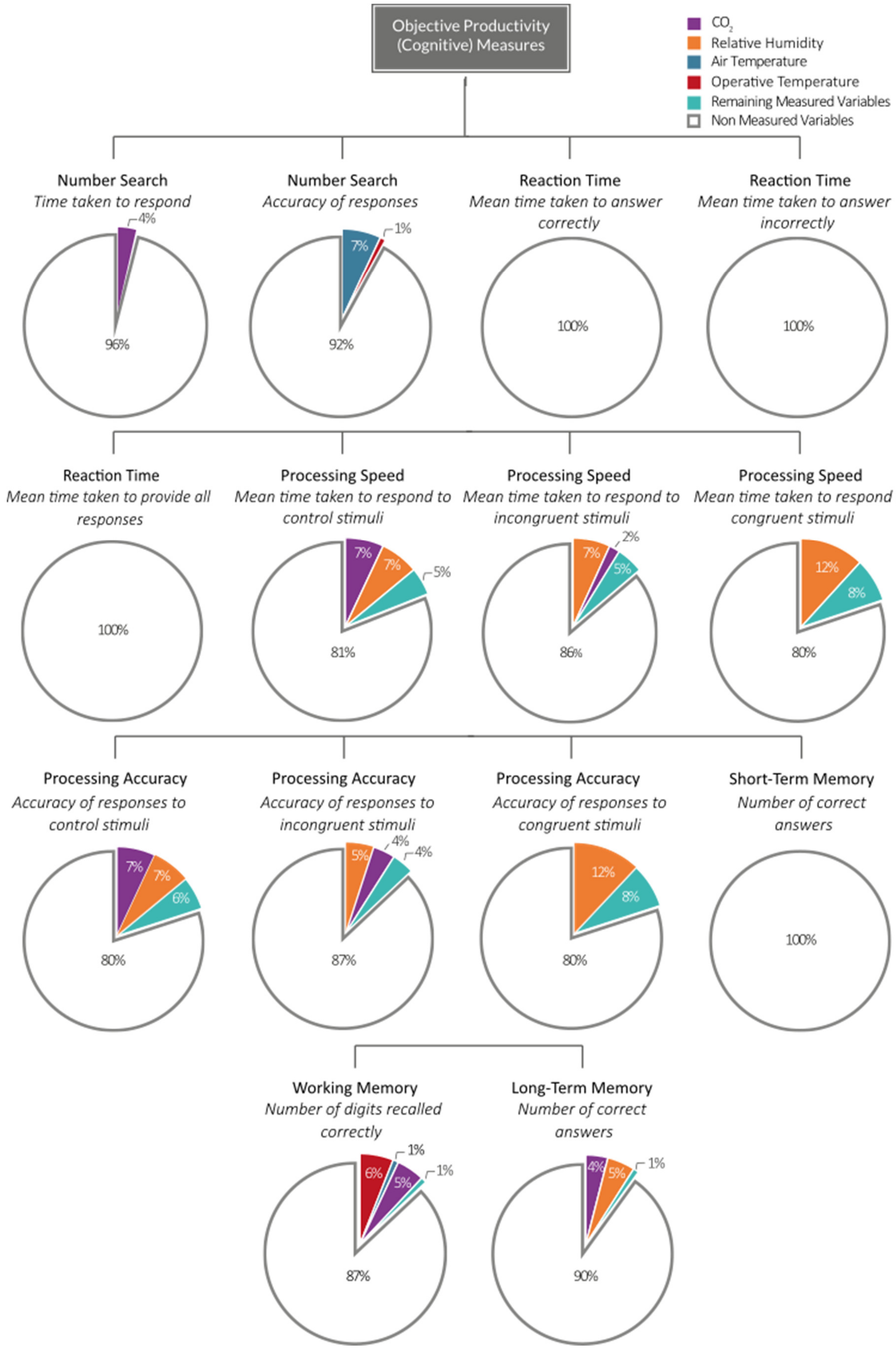

Figure 76. Cognitive Function Objective Productivity Measures and the contributing variances

Ten out of the fourteen cognitive function measures (or four out of the six tests given) produced a significant regression model. In eight out of the ten measures, all of the internal objective environmental variables (IVs) contributed variance in the performance of the participants. In the remaining two measures (for the number search test), only temperature (air and operative) and CO_2 levels varied the performance of the participants. Figure 76 summarises which IVs contributed and what proportion of variation they explained in each measure as indicated by the R^2 and the change in R^2 in the hierarchical regressions produced. The measures that produced a non-significant regression are represented in Figure 76 by a pie chart where 100% of the variance is explained by the 'Non-Measured Variables'. The IVs contributed between 4 - 20% of the variance overall, leaving 96 - 80% of the variance unaccounted for.

In Figure 76, it is observed that overall relative humidity and CO_2 were the most frequent singular IVs that had a varied level of participant performance for the cognitive function tasks. These contributed between 5 - 12% and 2 - 7% respectively to seven out of the ten significant measures. Relative humidity contributed the most variance to five out of the ten measures. For the number search task, which tests visual acuity, the CO_2 levels varied the participants' speed in responding to the task (by 4%). Temperature (air and operative) varied the accuracy of responses by 8% in total. Relative humidity and CO_2 were the only singular IVs that affected processing speed and accuracy. The percentage of variation differed depending on the stimuli being assessed. Relative humidity contributed to all of the processing speed and accuracy measures by 7 - 12% whereas CO_2 only varied the participants' responses to the control and incongruent stimuli (by 2 - 7%). In each of the processing speed and accuracy measures, a combination of the 'Remaining Variables Measured' IVs additionally provided variance. The participants' responses to the long-term memory test were also affected by relative humidity, $CO_{2,}$ and a combination of the 'Remaining Variables Measured' (lux levels, air and operative temperature and dBA). Relative humidity contributed 5%, CO_2 contributed 4%, and the remaining variables contributed 1%. Lastly, in the working memory test, operative temperature and CO_2 provided 6% and 5% respectively, and air temperature and the remaining IVs (lux level, dBA, and relative humidity) both contributed an additional 1%.

The significant Std.β coefficients identified that:

- A one standard deviation increase in air temperature (Std.β = 0.26, SD = 1.6°C) predicted the participants taking longer to complete the number search task (SD = 3.8 seconds) when all other IVs were held constant.

- A 1.6°C increase in air temperature predicted the participants taking 1 second longer in the number search task when all other environmental conditions remained the same.

- A one standard deviation increase in CO_2 (Std.β = 0.20, SD = 469 ppm) predicted a better accuracy score in the number search task (SD = 40%) when all other IVs were held constant.
  - A 469 ppm increase in CO_2 level predicted the participants achieving an 8% better accuracy score in the number search test when all other environmental conditions remained the same.

- In the first model, a one standard deviation increase in CO_2 level (Std.β = -0.26, SD = 469 ppm) predicted a quicker processing speed to the control stimuli (SD = 0.21 seconds) when all other IVs were held constant. However, when all variables were included in the model, a one standard deviation increase in relative humidity (Std.β = -0.31, SD = 5%) predicted a quicker processing speed to the control stimuli and a one standard deviation increase in lux levels (Std.β = 0.21, SD = 259 lux) predicted a slower processing speed. Relative humidity had the greatest predictive power (Std.β = -0.31). The results suggest that:
  - A 5% increase in relative humidity predicted a 0.06 second quicker processing speed to the control stimuli when all other environmental conditions remained the same.

- A one standard deviation increase in relative humidity (Std.β = -0.28, SD = 5%) predicted a quicker processing speed to the incongruent stimuli (SD = 0.31 seconds) when all other IVs were held constant. Additionally, a one standard deviation increase in lux levels (Std.β = 0.22, SD = 259 lux) predicted a slower processing speed to the incongruent stimuli. Relative humidity had the greatest predictive power (Std.β = -0.28). The results suggest that:
  - A 5% increase in relative humidity predicted a 0.08 second quicker processing speed to the incongruent stimuli when all other environmental conditions remained the same.

- A one standard deviation increase in relative humidity (Std.β = -0.36, SD = 5%) predicted a quicker processing speed to the congruent stimuli (SD = 0.22 seconds) when all other IVs were held constant. Additionally, a one standard deviation increase in lux levels (Std.β = 0.21, SD = 259 lux) predicted a slower processing speed. Relative humidity had the greatest predictive power (Std.β = -0.36). The results overall suggest that:

- ➢ A 5% increase in relative humidity predicted a 0.08 second quicker processing speed to the congruent stimuli when all other environmental conditions remained the same.

- A one standard deviation increase relative humidity (Std.β = -0.32, SD = 5%) or CO_2 (Std.β = -0.18, SD = 468 ppm) predicted a worse accuracy score to the control stimuli (SD = 3%) when all other IVs were held constant. Additionally, a one standard deviation increase in lux levels (Std.β = 0.21, SD = 259 lux) resulted in a better accuracy score. Relative humidity had the greatest predictive power (Std.β = -0.32). The results overall suggest that:
  - ➢ A 5% increase in relative humidity predicted a 3% worse accuracy score to the control stimuli when all other environmental conditions remained the same.

- A one standard deviation increase in relative humidity (Std.β = -0.24, SD = 5%) predicted a worse accuracy score to the incongruent stimuli within the Stroop task (SD = 20%) when all other IVs were held constant. Additionally, a one standard deviation increase in lux levels (Std.β = 0.21, SD = 259 lux) predicted a better accuracy score. Relative humidity (Std.β = -0.24) and lux levels (Std.β = 0.21) had a similar predictive power. The results suggest that:
  - ➢ A 5% increase in relative humidity predicted a 4.8% worse accuracy score to the incongruent stimuli. However, an increase of 259 lux also predicted a 4.2% better accuracy score when all other internal environment conditions remained the same.

- A one standard deviation increase in relative humidity (Std.β = -0.36, SD = 5%) predicted a worse accuracy score to the congruent stimuli within the Stroop task (SD = 3%) when all other IVs were held constant. Additionally, a one standard deviation increase in lux levels (Std.β = 0.21, SD = 259 lux) predicted a better accuracy score. Relative humidity had the greatest predictive power. The results suggest that:

- A 5% increase in relative humidity predicted a 3% worse accuracy score to the congruent stimuli when all other internal environment conditions remained the same.

- A one standard deviation increase in operative temperature (Std.β = 0.27, SD = 3°C) predicted a better working memory score (SD = 1.94, on a scale of 0 to 8) when all other IVs were held constant. However, when all variables were included in the model, a one standard deviation increase in CO_2 alone (Std.β = 0.23, SD = 468 ppm) resulted in a better score. Operative temperature (Std.β = 0.27) and CO_2 (Std.β = 0.23) predictive powers were relatively similar. The results suggest that:
  - A 3°C increase in operative temperature or a 468 ppm increase in CO_2 predicted a 0.52 or a 0.45 better score in the working memory test respectively when all other internal environment conditions remained the same.

- A one standard deviation increase in CO_2 (Std.β = -0.19, SD = 468 ppm) predicted a worse long-term memory score (SD = 3.48, on a scale of 0 to 30) when all other IVs were held constant. However, when all variables were included in the model, a one standard deviation increase in relative humidity (Std.β = -0.24, SD = 5%) alone predicted a worse long-term memory score. CO_2 (Std.β = -0.19) and relative humidity (Std.β = -0.24) had similar predictive powers and the results suggest that:
  - A 468 ppm increase in CO_2 or a 5% increase in relative humidity predicted a 0.66 or a 0.84 worse long-term memory score respectively when all other internal environment conditions remained the same.

One of the seven work type test measures and eleven of the fourteen cognitive function measures were varied by the internal environment conditions. dBA and lux levels were the only IVs that did not vary the participants' performance in the tasks as a singular IV. CO_2 level was the most frequent significant single IV that affected the participants' performance on the tasks. This varied the participants' text typing speed, response times, the accuracy of their responses, and both their working and long-term memory. Increases in CO_2 level have been previously found to negatively affect cognitive performance in the work of Allen et al. (2016) and Satish et al. (2012a, 2012b). In these studies, different tests were undertaken and increases in CO_2 level were related to a decrease in decision-making abilities (CIBSE, 2020). In this study increases in CO_2 levels negatively affected long-term memory but controversially positively affected working memory and the accuracy of the responses in the number search test.

Surprisingly, the variations in relative humidity affected the participants' performance in seven out of ten significant cognitive function measures, specifically those testing processing speed, accuracy and long-term memory. There is no existing research that identifies how relative humidity alters an individual's performance. Relative humidity often goes unmonitored or is controlled within productivity research (Lan and Lian, 2009; Wargocki et al., 2000, 2006). Relative humidity is usually inversely correlated with air temperature and is difficult to control in naturally ventilated environments. Too high or too low a level of humidity have been assessed to determine how they impact people's health and both too high and too low of a level of humidity can irritate the eyes and cause skin dryness, and other similar symptoms. In extreme cases, it can contribute to breathing difficulties (CIBSE, 2020). Without the support of further research literature in this area, it is hard to corroborate this study's finding.

Operative and air temperature varied participants' performance in the tasks by 1 - 7% for three of the tasks, specifically text typing speed, the accuracy of the responses to the number search task (a measure of visual acuity), and the participants' working memory scores. Increases in temperature are known to negatively affect occupant productivity. However, the previous research produced conflicting results in relation to temperature affecting text typing speed. Lan et al. (2011) found that an increase in air temperature (from 22°C to 30°C) in a simulated 'office' laboratory improved typing speed (without feedback of errors), although the results were not significant. Whereas a study conducted in real-world conditions found that nurses' data processing was negatively affected by 16% when the temperature exceeded 25.4°C (Federspiel et al., 2004). In this study, the Std β. identified a 3°C increase in operative temperature predicting the participants typing 3 less words per minute (WPM). The mean text typing speed across the entire period was 45 WPM and a reduction of 3 WPM suggests that a 3°C increase in operative temperature reduced the text typing performance by 7%.

An increase in air temperature also predicted the participants taking longer to respond to the number search task and an increase in operative temperature improved their working memory performance. The former result agrees with the work of Seppänen et al. (2006) who identified through a meta-analysis of 23 studies that used data processing as a measure of objective productivity. They concluded that increases in air temperature above

24°C negatively affected performance. However, the change in performance in working memory is surprising. Lan and Lian (2009) tested a broad range of cognitive tests on 12 participants in differing air temperatures (12°C, 21°C, and 28°C). It was concluded that working memory was negatively affected by the increases in temperature. However, a statistical difference in performance was not found between all of the temperature bands.

Increases in lux levels negatively affected response times but positively affected the accuracy on the processing speed and accuracy test. Performance on this test has not been previously influenced by participants' experience of internal illuminance (de Vries et al., 2018), although experiences of glare have been found to negatively affect the performance of occupants on tasks that require memory and visual acuity (Heschong Mahone Group, 2003). Surprisingly, the participants' performance on the number search task was not affected by the variation in lux levels experienced even though the task was executed in a similar way to the task carried out by (Heschong Mahone Group, 2003). However, the building type, layout, and conditions experienced differed between the studies.

4.5.4 Comparing Open and Closed Blind Conditions (Objective C and D)

Box plots and two other different statistical methods were used to compare the differences between the data collected in the two conditions, specifically blinds open, and blinds closed. Box plots were used to identify the Mean, Median, Min and Max of the internal and external environmental conditions when the blinds were either open or closed. This was examined in both offices and across all of the test sessions. A Chi-square (χ^2) test was used to identify whether there were differences in the distribution of the responses provided by the participants in either the open or closed conditions to the questions (Objective C). Lastly, a paired t-Test was used to investigate whether there was a statistical difference between each individual participants' mean response to the question and test data, and if there were any differences between the mean internal environment conditions when they were in either a blind open or blind closed conditions (Objective D2). To ensure this was a fair comparison, the paired t-Test was also used to identify whether there was a statistically significant difference between the external objective environmental conditions (Objective D1). Box plots were produced to provide an overall indication of the external weather conditions experienced when the participants were in either condition.

The paired t-Test method of analysis differs from the χ^2 as the participants' mean response in an open blind condition were compared to their own response in the closed blind condition. χ^2 compares the distribution of the group of participant responses in the open blind conditions with the group of participant responses in the closed blind conditions.

Below is an explanation of the outputs of the box plots and the two statistical methods. In the following sections, the significant χ^2 and results approaching significance ($p < 0.05$) are reported and bar charts are used to present and identify the differences in distribution (χ^2). Additionally, the significant ($p < 0.05$) and non-significant paired t-Test results have also been tabulated. The differences between the mean responses in the t-Test have been used to interpret how the participants responded between the two conditions.

Box plots

Each data point in the box plots represents the mean environment measure over the duration of time that it took each participant to complete the tests and questionnaire (i.e., the test session means for each participant). Each box plot presents the overall mean (Δ), median (central line), lower (bottom line of the box) and upper quartiles (upper line of the box), and the minimum (bottom error bar) and maximum (top error bar) data points collected when the blinds were either open (orange box plot) or closed (blue box plot).

Chi-square

The output of the Chi-square is a χ^2 statistic and an associated significance level. The χ^2 statistic tells us how much of a difference exists between the data collected and what we would expect to see if there was no relationship. A significant result ($p < 0.05$) indicates that this result was not found by chance. This statistical technique can only be used to assess the differences between the categorical data. Therefore, the objective productivity measures and the internal objective environment measures could not be assessed using this method. In total, 177 - 179 questionnaire responses were evaluated which were split into two groups: the participants in the closed blind conditions (N = 97- 99[38]) and the participants in the open blind conditions (N= 80). Additionally, this method of analysis was only considered to be appropriate as the box plot analysis of the external weather data found that the overall external environment conditions were not notably different when each group of participants responded to the tests and questionnaires in either the open or closed blind conditions.

Paired t-Test

A paired t-Test compares the two sets of data that are dependent (i.e., they are related) to identify whether the two sets of data significantly differ ($p < 0.05$). Prior to conducting the paired t-Test, it was important to first determine whether each participant responded to

[38] The N varies as two participants did not complete the full test battery on one occasion and two participants did not complete the full test battery on another occasion.

the tests and questions if there was a reasonable variation of external environmental conditions within each of the conditions (open or closed blinds) (Objective D1). To establish if each individual occupant was exposed to a fair variation of external weather conditions, a means paired t-Test was conducted that compared the mean external environmental conditions of each participant between the two interventions. A null hypothesis was reached identifying that each individual participant answered the test battery within a fair variation of external weather conditions between the open and closed blind conditions. The limitation of this method of analysis is that the N total was low as there were only 19 participants in total.

4.5.4.1 Objective External Environment

Figure 77 - Figure 79 show there was little difference in either the mean or ranges (difference between the minimum error bar and the maximum error bar) in the external environmental conditions experienced when the data was collected in the open and closed blind conditions.

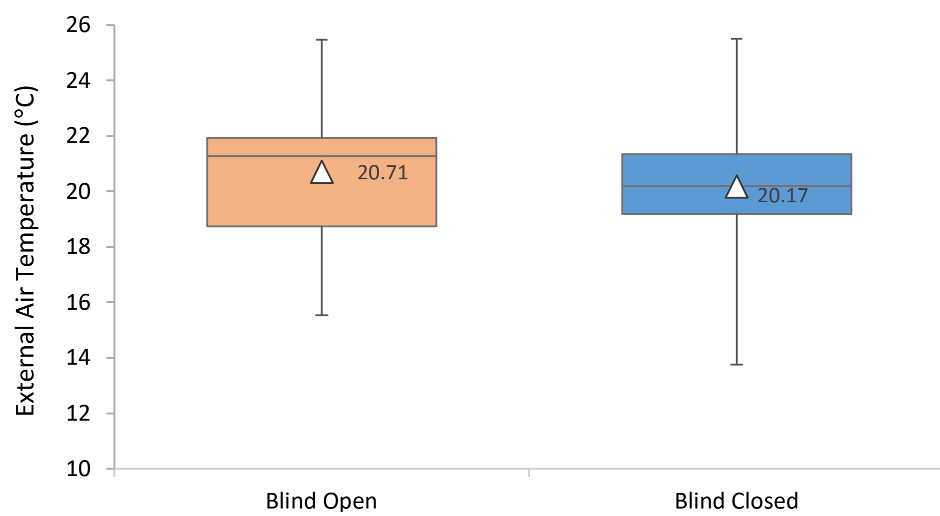

Figure 77. Test Session Mean External Air Temperature (° C) between the blind open (N = 80) and closed (N = 111) conditions for each participant (Δ = Mean).

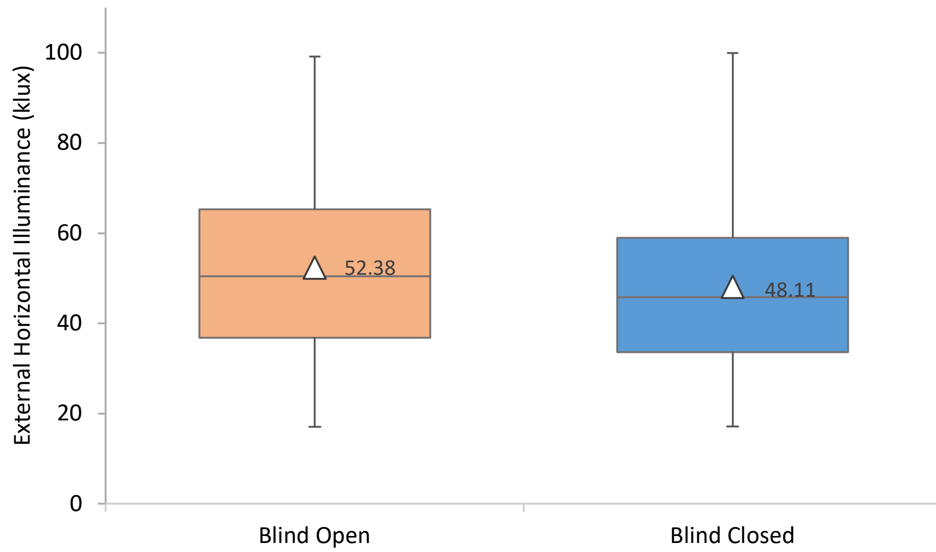

Figure 78. Test Session Mean External Horizontal Illuminance (klux) between the blind open (N = 80) and closed (N = 111) conditions for each participant (Δ = Mean).

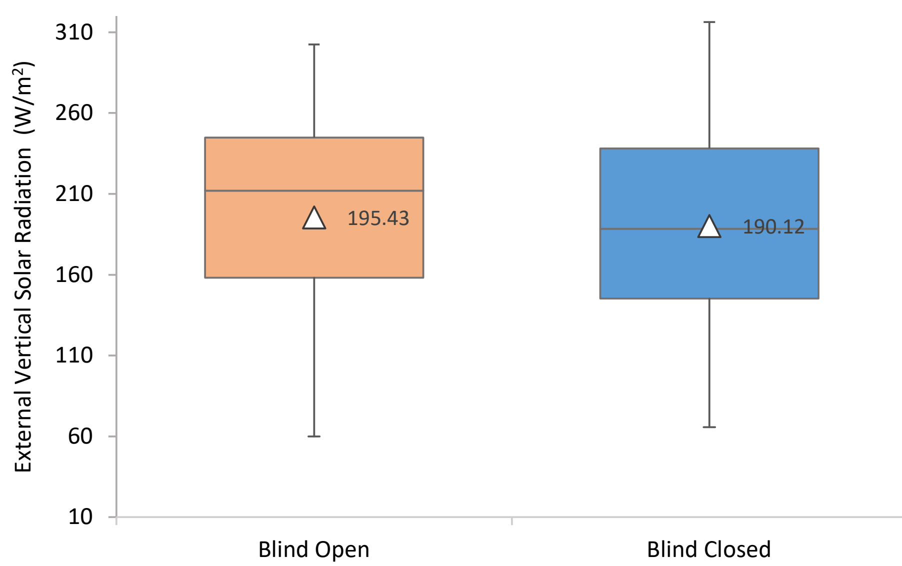

Figure 79. Test Session Mean External Vertical Solar Radiation (w/m^2) during the test sessions between the blind open (N = 80) and closed (N = 111) conditions for each participant (Δ = Mean).

4.5.4.2 Objective Internal Environment

The box plots in Figure 80 - Figure 85 identify the recommended comfort thresholds that have been plotted with dashed horizontal lines (where appropriate) on each box plot. The comfort thresholds refer to the values provided in Chapter 2, Table 3 in Section 2.2 (p. 14) in relation to the offices.

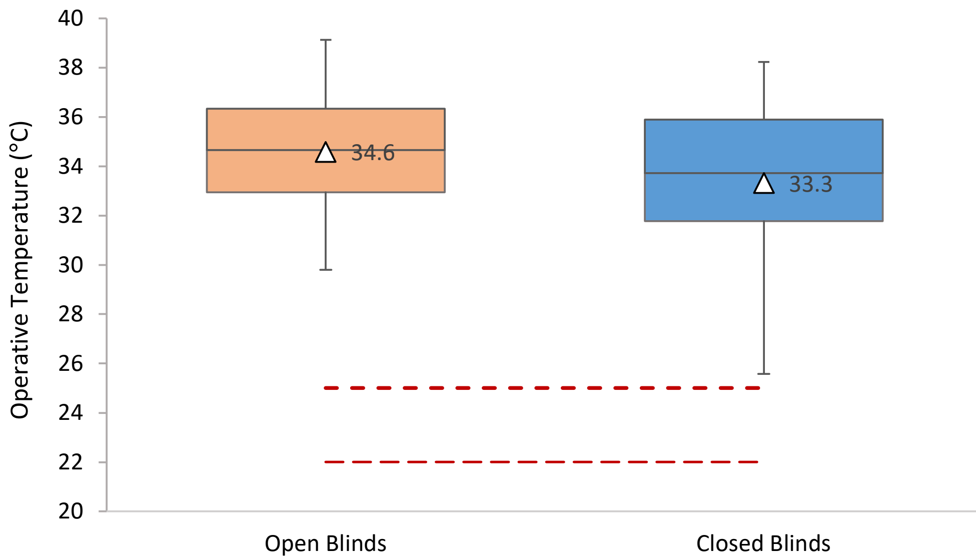

Figure 80. Test Session Mean Operative Temperature between the open (N = 66) and closed (N = 102) blind conditions for each participant (dashed line = comfort threshold, Δ = Mean).

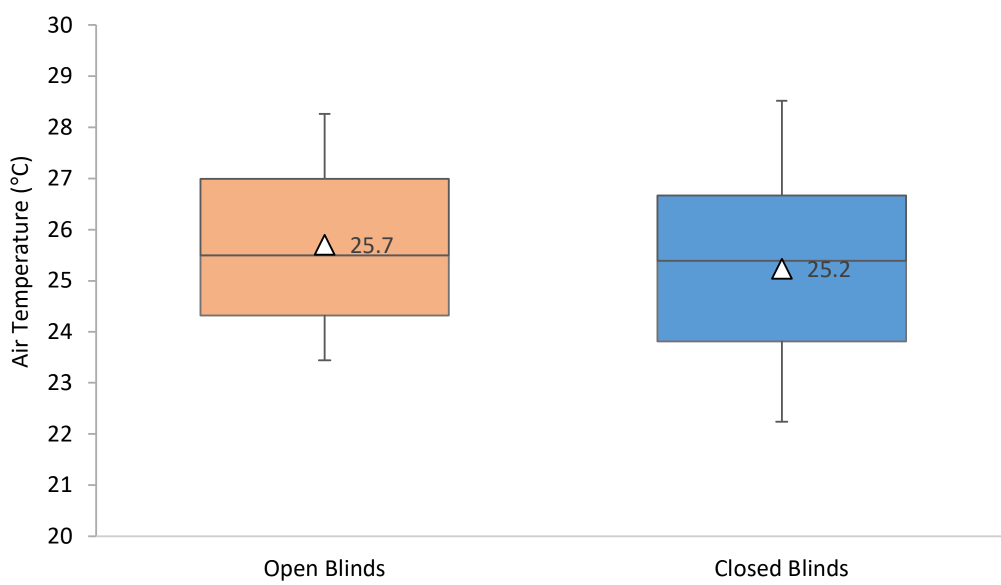

Figure 81. Test Session Mean Air Temperature between the open (N = 74) and closed (N = 111) blind conditions for each participant (Δ = Mean).

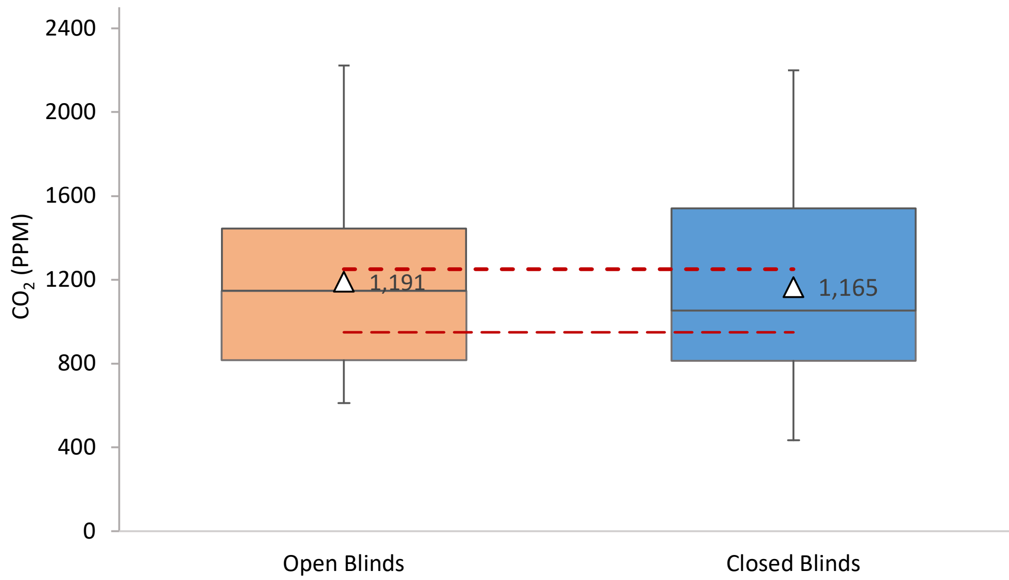

Figure 82. Test Session Mean CO_2 Levels (PPM) between the open (N = 62) and closed (N = 103) blind conditions for each participant (dashed line = comfort threshold, Δ = Mean).

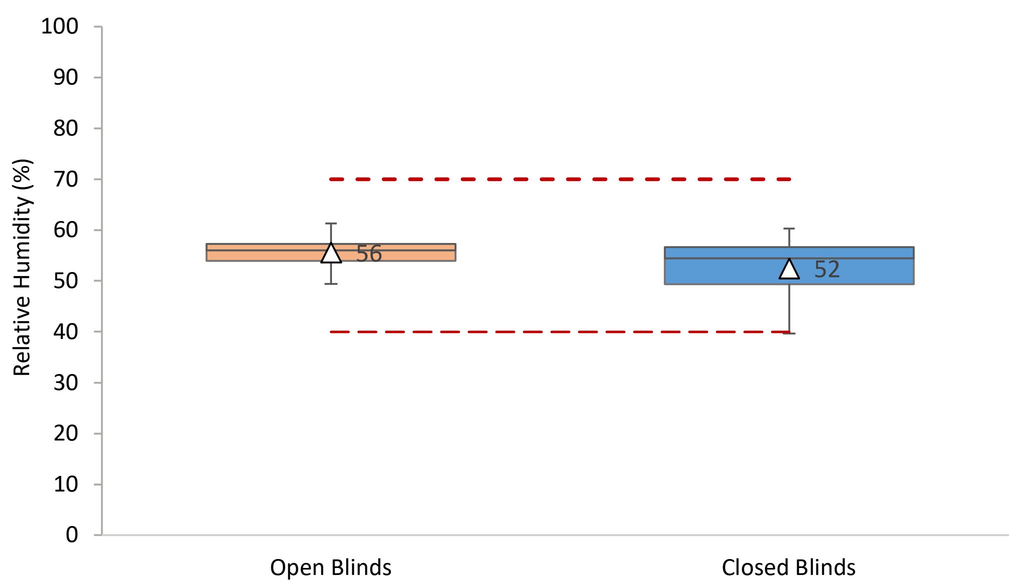

Figure 83. Test Session Mean Relative Humidity between the open (N = 74) and closed (N = 111) blind conditions for each participant (dashed line = comfort threshold, Δ = Mean).

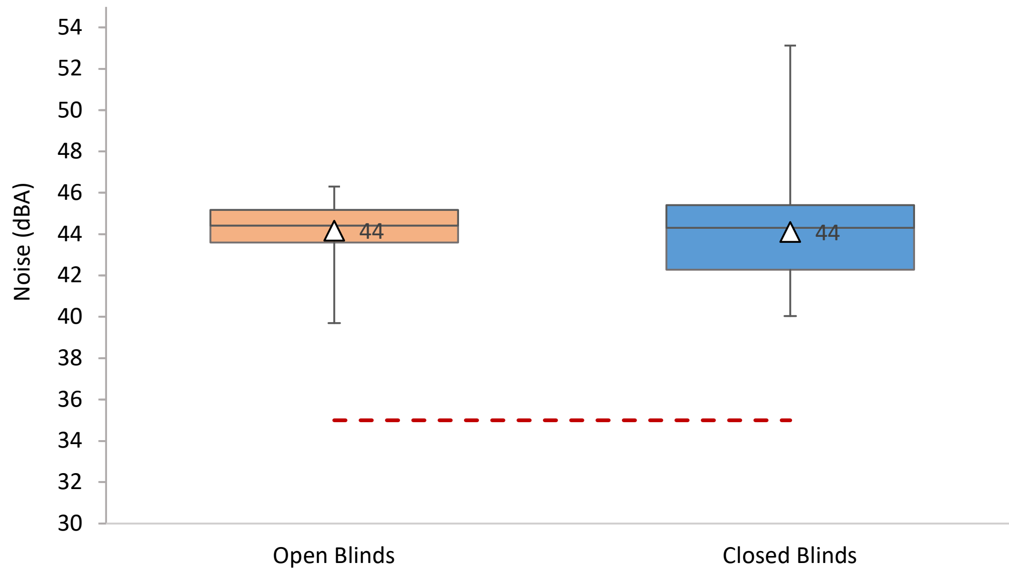

Figure 84. Test Session Mean Noise Level (dBA) between the open (N = 74) and closed (N = 111) blind conditions for each participant (dashed line = comfort threshold, Δ = Mean).

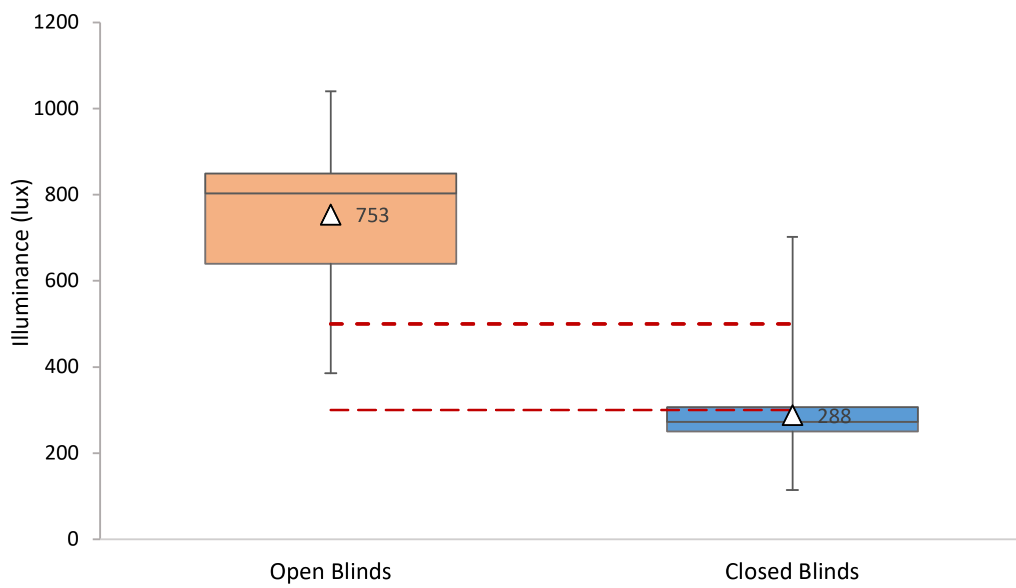

Figure 85. Test Session Mean Illuminance between the open (N = 74) and closed blind (N = 111) conditions for each participant (dashed line = comfort threshold, Δ = Mean).

When comparing the mean internal environmental conditions between the interventions (blinds open and blinds closed), the box plots infer that there were large differences in internal illuminance (MΔ = 466 lux) and a slight difference in internal operative temperatures (MΔ = 1.27°C). The difference in air temperature (MΔ = 0.5°C) was within the sensitivity range of the air temperature sensor (+/- 0.5°C), thus it can be considered negligible. There was also little difference found in the rest of the internal environment measures (CO_2, RH, and dBA) and out of all of the measures, only relative humidity remained between the comfort thresholds.

The internal illuminance conditions in the open blind conditions were almost consistently above the comfort threshold (i.e., > 500 lux) whereas in the closed blind conditions, the participants experienced internal illuminance levels that were above and below the comfort threshold (i.e., < 300 lux). The mean operative temperature exceeded the comfort threshold (> 25°C) in both conditions. However, the operative temperature box plots show that there was an overall shift in the temperatures experienced between the open and closed blind conditions. The M, Median, Min and Max, lower and upper quartile ranges in the open blind conditions are all higher than those experienced in the closed blind conditions. Notably there was a large shift in the minimum operative temperatures experienced which differed by approximately 7°C between the interventions. Interestingly, the difference between the minimum air temperatures was negligible (< 0.5°C). The differences in the temperature measures reflects the impact of the mean radiant temperature on the internal environment. As previously mentioned, operative temperature considers the impact of the changes in mean radiant temperature (emitted from radiant heat sources and surfaces), air temperature, and air velocity. Considering that we know that the internal air temperatures and air velocities were similar between the interventions, it suggests that the 7°C difference in the miniumum operative temperature measured is a result of the differences in the mean radiant temperature. Large differences are likely to be because the position of the blinds would have blocked solar radiation from entering the internal environment. However, the differences in the mean radiant temperatures may also be caused by differences in occupancy as people emit radiant heat, as does the equipment that they use (e.g., computers).

Overall, the internal environmental data suggests that the participants in the open blind conditions were subjected to a greater variety of internal illuminance conditions that would likely make them feel both comfortable and uncomfortable. Additionally, even though the internal temperatures were relatively similar, the occupants in both conditions were exposed to overly warm environments throughout the duration of the test sessions.

However, the participants in the closed blind conditions experienced slightly cooler internal conditions.

Table 36. Paired t-Test results of the Objective Environment Measures (N=17 or 19)

Measure	Closed Blind Mean *(SD)*	Open Blind Mean *(SD)*	95% Confidence Interval of Difference		t	df	Sig. (2-tailed)
			Lower	Upper			
Lux	284.69 *38.38*	744.85 *112.03*	410.38	509.93	19.42	18	< 0.001***
Operative Temperature	33.36 *1.66*	34.87 *2.36*	0.79	2.22	4.46	16	< 0.001***
Air Temperature	25.32 *0.95*	25.85 *2.44*	0.19	0.87	3.29	18	0.04*
Relative Humidity	52.90 *3.44*	55.26 *2.45*	0.39	5.11	1.81	18	0.09
dBA	43.92 *1.29*	44.24 *0.56*	0.35	0.98	1.00	18	0.33
CO_2	1229.84 *356.45*	1241.12 *281.01*	83.15	105.71	0.25	18	0.81

*** $p < 0.001$ * $p < 0.05$

The paired t-Test analysis (Table 36) found that there was a significant difference in the illuminance ($p < 0.001$), operative ($p < 0.001$), and air temperatures ($p < 0.05$) that the participants were exposed to between the two conditions. These results imply that the participants in open blind conditions experienced higher lux levels, operative temperatures, and air temperatures than the participants in the closed blind conditions. The lower and upper 95% confidence intervals identify how much greater / higher the internal environment conditions were in the open blind conditions. However, when considering the sensitivity of the sensors with the calculated 95% confidence interval of difference, it can be observed that there was a very small difference between the temperatures experienced. The sensitivity of the temperature sensors was +/- 0.5°C which suggests that the air temperatures were at most 0.4°C warmer in the open blind conditions than in the closed blind conditions. This difference can be considered negligible. The difference in operative temperature is slightly larger when taking into account the sensitivity of the sensor which suggests that the operative temperature was at most 1.7°C warmer in the open blind conditions.

All other internal environmental variables were non-significant which suggests that the position of the blinds did not affect the relative humidity, noise levels, or CO_2 levels. This was expected as even though some types of blinds can affect the internal acoustics of a room, those installed were acoustically transparent.

4.5.4.3 Subjective Perceptions of the Internal Environment

4.5.4.3.1 Thermal Comfort

There were no significant differences between the participants' sensation, preference, or acceptability of the air temperature when the distribution of the responses was compared between the open and closed blind conditions in the χ^2 analysis. This suggests that as a group, they responded in the same way or so similarly that no statistical significance was found. However, significant differences were found when the participant's mean responses were analysed using the t-Tests. The tests identified that in the open blind conditions, they felt hotter and preferred cooler conditions.

Table 37. Paired t-Test results of the Thermal Comfort Measures (N=19)

Measure	Closed Blind Mean *(SD)*	Open Blind Mean *(SD)*	t	df	Sig. (2-tailed)
Air Temperature Sensation	4.93 *(0.79)*	5.32 *(0.70)*	2.77	18	0.01*
Air Temperature Preference	1.37 *(0.39)*	1.22 *(0.36)*	2.56	18	0.02*
Air Temperature Acceptability	2.69 *(0.41)*	2.55 *(0.45)*	1.59	18	0.13

* $p < 0.05$

The t-Test results above imply that as individuals, they appropriately identified a thermal difference between the open and closed blind conditions. When comparing the mean difference in temperatures between the two groups of participants (see Section 4.5.4.1, p 231), there was a negligible difference in the mean air temperatures (< 0.5°C) and a relatively small difference in internal operative temperature (1.2°C). The small difference in objective temperatures may explain why no statistical significance was reached between the groups of responses. When comparing the participants' individual exposure to the operative temperatures, the mean difference was slightly higher (1.5°C) and the 95% confidence interval suggested that each participant's exposure varied consistently by between 0.8 and 2.2°C (+/- 0.5°C when considering the sensitivity of the sensor). The lack of significance in the group distributions may also be explained by too much variation in the dataset. A person's physiological response to heat, which subsequently affects their perceptions, differs between the individual factors such as age, gender, ethnicity, underlying health conditions, clothing level, and their activity level, all of which affect the individual's sensitivity to changes in the environmental conditions. These variations between individuals may have created too much 'noise' within the groups of responses to identify a significant difference in the thermal perceptions when the responses were grouped together and compared. The relationships between the participants' perception of the thermal conditions and the mean air temperature on each testing day have been further explored in Section 4.5.5.2.1 (p. 259). The relationships between the participants' thermal sensation, preference and acceptability responses have also been explored further in Section 4.5.5.1.1 (p. 251).

4.5.4.3.2 Air Quality

One of the six air quality measures found there to be a significantly different distribution of responses between the blind open and blind closed conditions. The participants' sensation of air humidity, χ^2 (6, N = 177) = 12.60, *p* =.03, differed and the distribution in Figure 86 suggests that the participants in the open blind conditions perceived conditions as less humid than those in closed blind conditions.

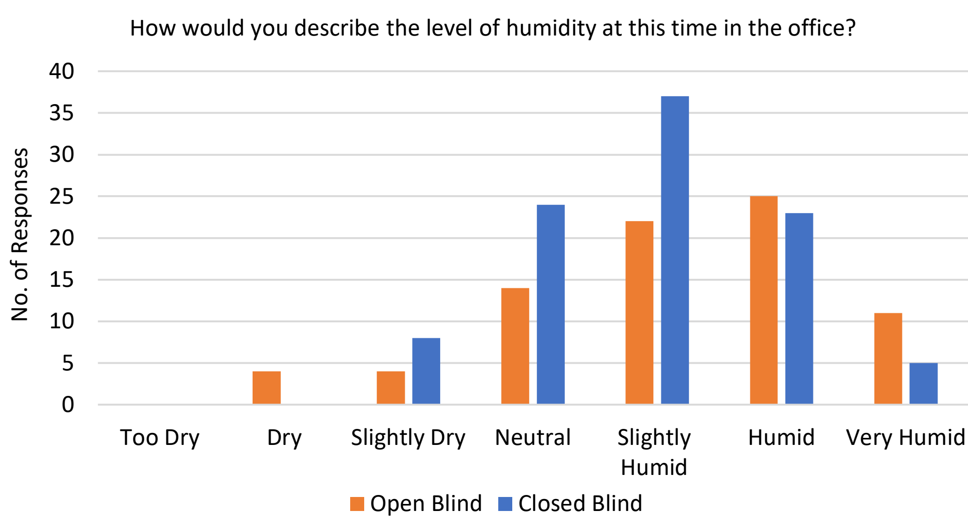

Figure 86. Humidity sensation between the open (N = 80) and closed blind (N = 97) conditions.

When the participant's mean responses were assessed, there was found to be a significant difference between the perceptions of air freshness between the blind open and blind closed conditions. The direction of the means suggest that the participants perceived the air in the closed blind rooms to be fresher compared to the air in the room when the blind was open. All other air quality measures were non-significant. The results of the t-Tests are presented in Table 38.

Table 38. Paired t-Test results of Air Quality Measures (N=19)

Measure	Closed Blind Mean *(SD)*	Open Blind Mean *(SD)*	t	df	Sig. (2-tailed)
Humidity Sensation	4.96 *0.64*	5.19 *0.77*	1.37	18	0.19
Humidity Preference	1.32 *0.40*	1.31 *0.41*	0.14	18	0.89
Air Freshness Sensation	2.44 *0.69*	2.14 *0.81*	2.13	18	0.05*
Air Freshness Preference	2.81 *0.27*	2.89 *0.25*	0.99	18	0.33
Air Odour/Fragrance Sensation	3.58 *0.54*	3.54 *0.63*	0.35	18	0.73
Air Odour / Fragrance Preference	2.68 *0.34*	2.65 *0.39*	0.55	18	0.59

* $p < 0.05$

These results are unexpected because the blind position is not known to directly influence perceptions of air quality. The analysis of the objective internal measures found that there were no significant differences between relative humidity (p = 0.09), or CO_2 levels (p = 0.81) experienced by each participant in either condition (see Table 36). However, when considering the larger dataset, the hierarchical regressions (see Section 4.5.3.1.2, p. 193) identified that an increase in air temperature predicted a stuffier air freshness response and a more humid sensation response. Closing the blinds lowered the internal temperatures, thus we expected to find that when the blinds were closed, the participants' reported a less humid environment as opposed to the more humid response that was found. This result, whilst interesting, cannot be supported by the research literature and it was perhaps only found because of the narrow range of the relative humidity conditions that the participants were exposed to (which varied by a mean of < 5 %), according to the 95% interval of confidence reported in Table 38. The occupants were not able to identify a difference of < 5% in the relative humidity levels. Nevertheless, the finding that the air freshness is affected by the blind position can be supported by the described interrelationship between blind position, air temperature, and air quality. The relationship between temperature and air quality is also supported by the previous academic research that has identified that increases in air temperatures (and relative humidity levels) negatively affect the perceptions of air quality (Fang et al., 2004; Witterseh et al., 2004).

It has also been previously discussed (see Section 4.5.3.1.2, p. 193) that the opening and closing of the blind may also affect the amount of VOCs released by the surface finishes within the office. This is because increases in surface temperature enhance the release of VOCs (Kang et al., 2010; Kim et al., 2012). The inclusion of the measurements of VOCs would provide a greater understanding of the impact of blinds on internal air quality in future studies.

4.5.4.3.3 Acoustic Comfort

The distribution in responses to the one question assessing the participants' perception of noise produced an almost significant result, χ^2 (7, N = 177) =12.08, p =.06. The distribution of these results suggests that the participants in closed blind conditions felt that the noise levels were quieter (Figure 87). This was an interesting result as the shading fabric installed can be considered acoustically transparent and it would not have had a physical impact on the noise levels.

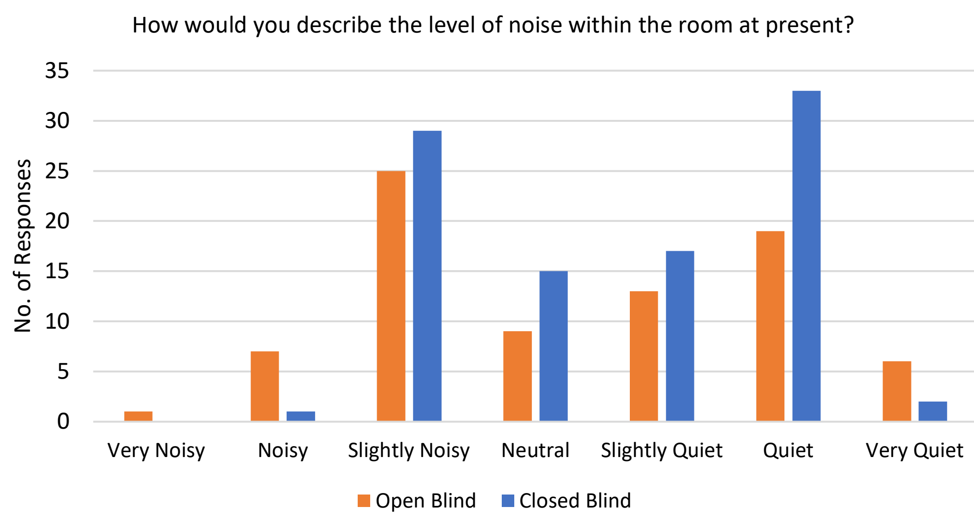

Figure 87. Noise sensation between the open (N = 80) and closed blind (N = 97) conditions.

The paired t-Test did not find there to be a statistically significant difference between the participants' mean responses, although the direction of the mean responses also suggested that the participants perceived the conditions to be quieter in the closed blind conditions overall.

Table 39. Paired t-Test results of the Acoustic Comfort Measure (N=19)

Measure	Closed Blind Mean *(SD)*	Open Blind Mean *(SD)*	t	df	Sig. (2-tailed)
Noise Sensation	4.54	4.33	1.14	18	0.27
	1.06	*1.12*			

The dBA measurements collected suggest that there was no difference in the noise levels between the open and closed blind conditions[39]. This supports the null hypothesis reached in both sets of results. However, it was interesting to see that there was some suggestion of a relationship between the perceptions of noise and the blind position in the χ^2. Considering that the air temperatures did not differ considerably between the two conditions, it is unlikely that the interrelationship between air temperature and noise perception would have contributed to the difference (i.e., increases in temperature resulting in louder perceptions of noise (Guan et al., 2020)). However, in the focus group (see Section 4.5.6.2, p. 284), the participants suggested that when they were in the closed blind conditions, there was a behavioural change in the occupants in the office. They commented that they were more focused and quieter which may explain why overall, the participants perceived the conditions to be quieter in the closed blind conditions. However, there was a bi-modal distribution of responses when the blinds were closed which may also be explained by the participants' different approaches to the testing in the two offices. In the focus group, it was also revealed that one office would start the tests at the same time to ensure that everyone was focused on the tests at the same time. In the other office, no such strategy was devised, and complaints were made by those participants, stating that they would get frustrated about being distracted or their inability to focus. Therefore, it is possible that the design of the study impacted the outcome of these results.

4.5.4.3.4 Visual Comfort

Overall, six out of the ten measures of visual comfort had significantly different distributions of responses between the blind conditions. Considering extending shading products attenuates incoming daylight, it was unsurprising to find a large number of significant differences between the two groups. The participants' perception of the brightness, χ^2 (7, N = 177) =98.98, p < .001, the acceptability of the level of brightness, χ^2 (5, N = 177) =33.34, p < .001, and the perception of how easy it was to read the questionnaire, χ^2 (6, N = 177) =26.80, p < .001, were all significantly different. Additionally, the participant's experience of glare issues, χ^2 (3, N = 177) = 33.34, p = .02, the source of the glare, χ^2 (3, N = 177) = 33.34, p = .02, and the participants' perception of the view, χ^2 (7, N = 177) =12.81, p = .05, were also found to be significantly different between the blind open and blind closed conditions.

[39] The mean dBA collected for all participants in both conditions were equal (44 dBA) and when the mean dBA levels for each participant were compared the paired t-Test suggested there was no significant difference between noise levels (p < 0.33).

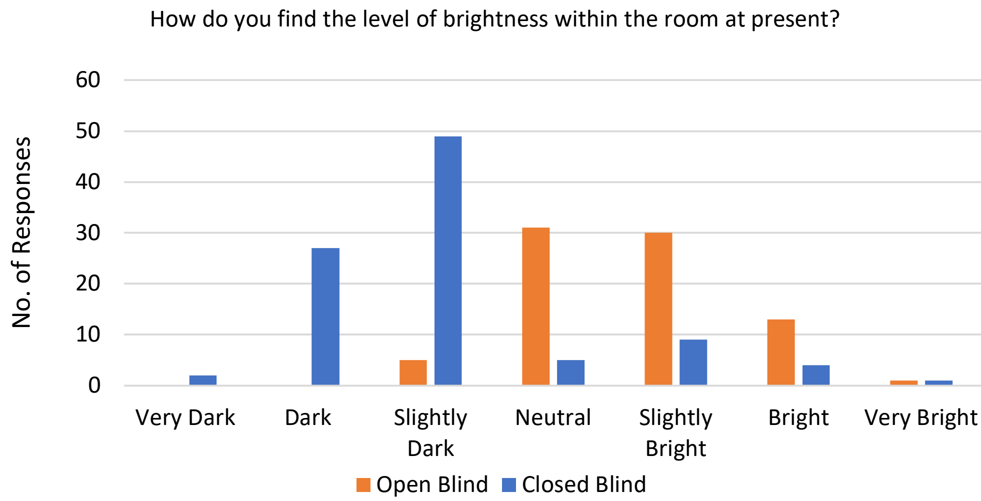

Figure 88. Lighting Sensation between the open (N = 80) and closed blind (N = 97) conditions.

The distribution of responses to the light sensation question in Figure 88 identified that the participants in the open blind conditions found the conditions to be brighter. However, oddly, fourteen participants identified that the conditions were either ‘Slightly Bright’, ‘Bright’ or ‘Very Bright’ when the blinds were closed. Generally when blinds are closed, the conditions are considered to be darker as they reduce the amount of incoming daylight and subsequently the internal illuminance. These results have been further explored in Section 4.5.5.2.2 (p. 262) by comparing the participants’ lighting sensation responses with the objective illuminance level.

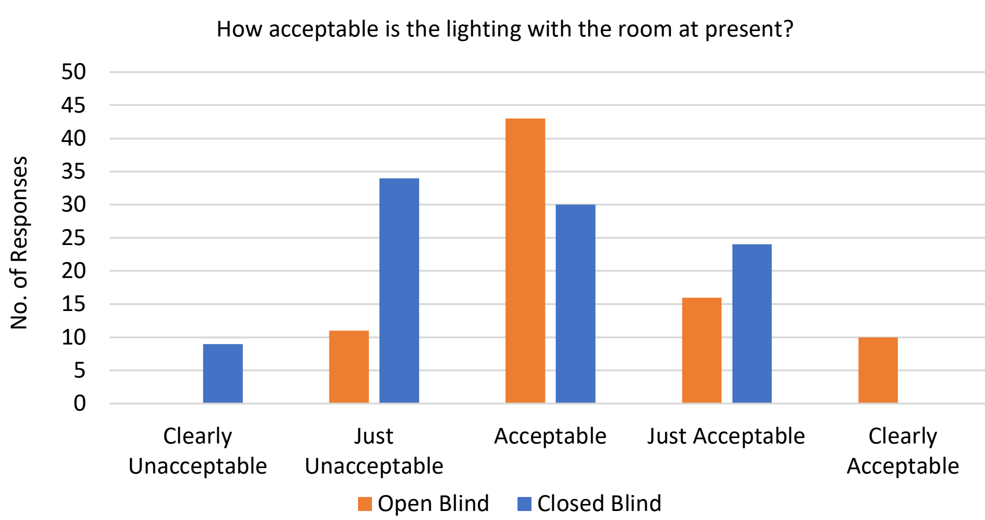

Figure 89. Lighting Acceptability between the open (N = 80) and closed blind (N = 97) conditions.

The participants’ responses to how acceptable the level of brightness was, has been presented in Figure 89. This shows that the participants in open blind conditions found the lighting to be more acceptable. The previous research also supports the finding that brighter conditions are generally more accepted and preferred by the occupants (Edwards and Torcellini, 2002; Silvester and Konstantinou, 2013).

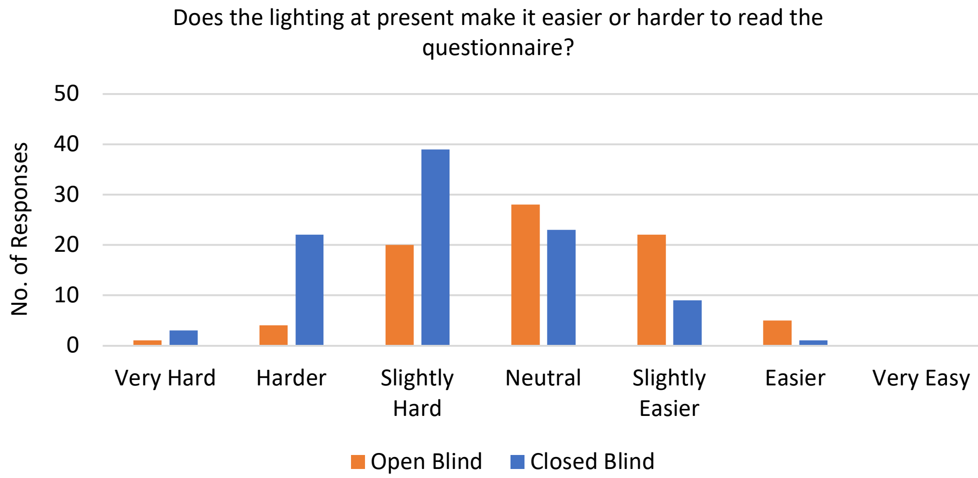

Figure 90. Visual Ease when reading the questionnaire between the open (N = 80) and closed blind (N = 97) conditions.

The distribution of responses in Figure 90 identifies that the participants in the open blind conditions found the questionnaire to be easier to read which is a result of the brighter conditions experienced when the blinds are retracted. Brighter conditions have been previously found to improve the ease of reading, reducing visual strain (Boyce, 2014; Viola et al., 2008).

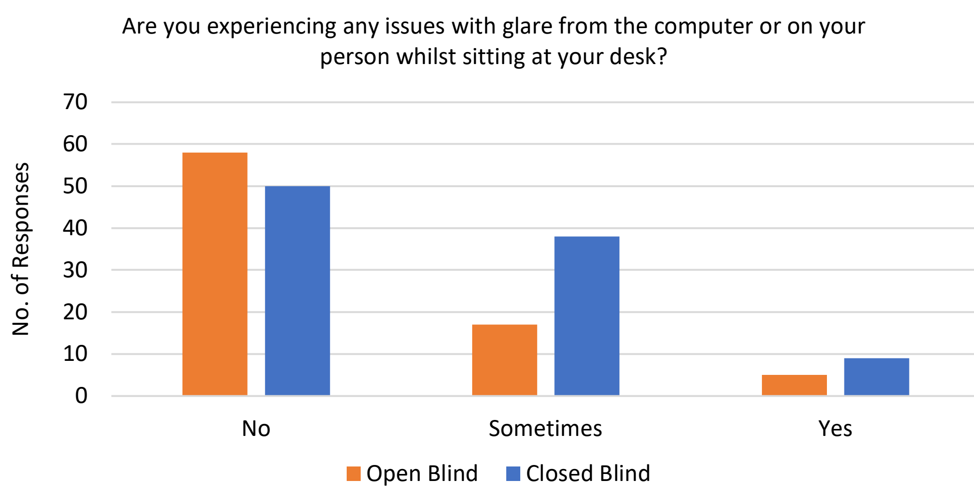

Figure 91. Identifiable Glare Issues between the open (N = 80) and closed blind (N = 97) conditions.

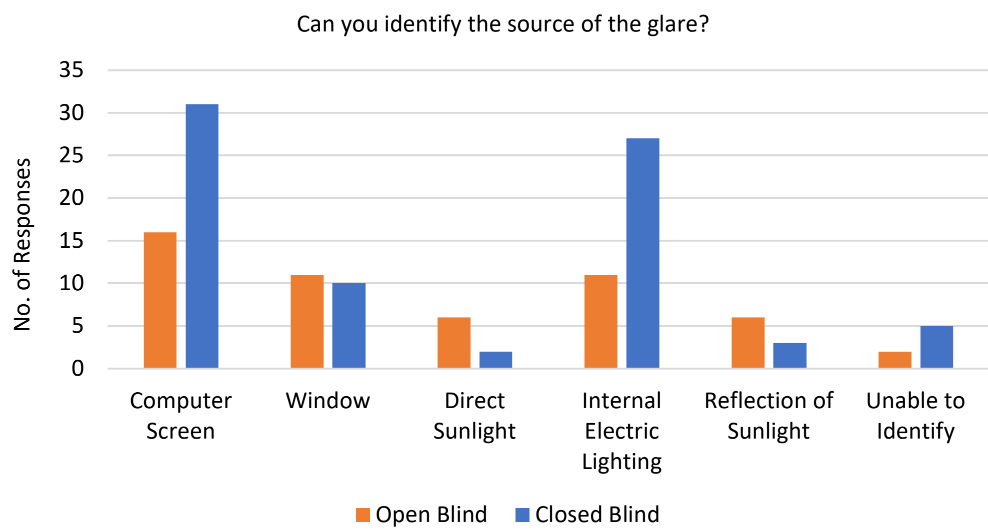

Figure 92. Glare Source between the open (N = 52) and closed blind (N = 78) conditions.

Figure 91 and Figure 92 identify that the participants with closed blinds experienced more glare issues and that these issues were most frequently related to the ‘computer screen’ or the ‘internal electric lighting’. This was an unexpected result as generally glare issues are considered to more frequently occur when the blinds are open and when the illuminance levels are high. However, they can also be perceived when there is an uneven distribution in illuminance around the visual task. We can speculate that closing the blinds in the offices reduced the peripheral illuminance and the light emitting from the electric lighting. The computer screen may have created too harsh a contrast between the visual task, the central field, and the peripheral area of the room which can contribute to visual discomfort and glare issues (Wouter et al., 2010). The reporting of glare issues in relation to the objective internal illuminance and the other visual comfort questions has been further investigated in Section 4.5.5.2.2 (p. 262).

Figure 93 identifies that the differences in distribution between the open and closed blind conditions in terms of participant satisfaction have the view that suggests that the participants in open blind conditions were more satisfied with the view. This makes logical sense as the blinds would have been open, providing a clear view out of the windows. Considering that all of the participants were in close proximity to a window, it is understandable that a significant result was found as when the blinds were closed, they would have partially obstructed the external view.

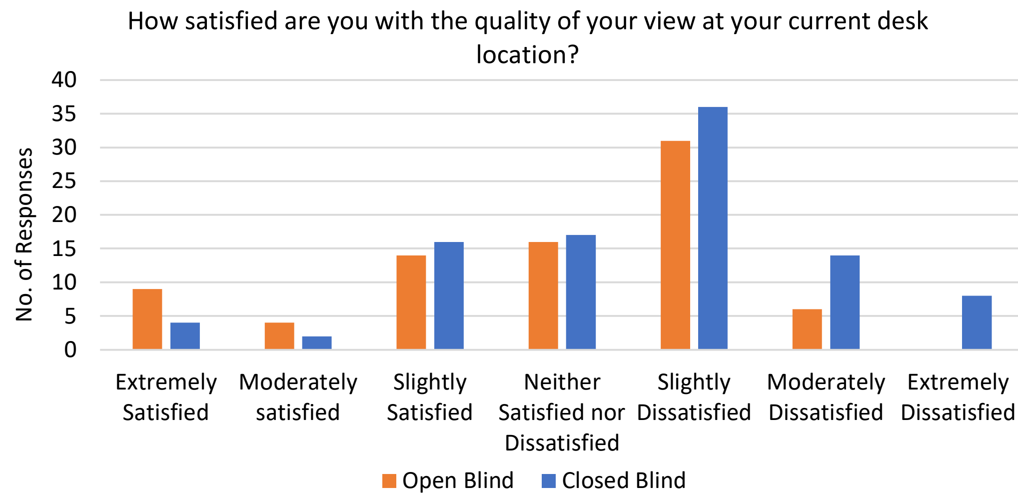

Figure 93. View Sensation/Satisfaction between the open (N = 80) and closed blind (N = 97) conditions.

The means paired t-Test identified that six out of the nine visual comfort measures were significantly different between the blind conditions. These results are shown in Table 40. Four of these results support the χ^2 results. Additionally, the paired t-Test found that the participants' lighting preference and the level of visual strain experienced differed between the two conditions.

Table 40. Paired t-Test results of the Visual Comfort Measures (N = 19 and 10)

Measure	Closed Blind Mean *(SD)*	Open Blind Mean *(SD)*	t	df	Sig. (2-tailed)
Lighting Sensation	3.17 *0.91*	4.71 *0.52*	6.74	18	< 0.001***
Lighting Preference	4.93 *0.79*	5.30 *0.69*	2.63	18	0.02*
Lighting Acceptability	2.74 *0.70*	3.23 *0.72*	2.68	18	0.02*
Visual Strain	1.85 *0.51*	1.71 *0.54*	2.61	18	0.02*
Visual Ease	3.21 *0.78*	3.99 *0.71*	4.39	18	< 0.001***
Identifiable Glare Issues	0.56 *0.54*	0.41 *0.51*	1.63	18	0.12
Magnitude of Glare	1.49 *0.74*	1.40 *0.57*	0.50	9	0.63
Glare Sensation	1.60 *0.64*	1.43 *0.38*	1.10	9	0.30
View Sensation	3.32 *1.22*	4.04 *1.27*	2.19	18	0.04*

* $p < 0.05$ *** $p < 0.001$

The means suggest that the participants in the open blind conditions preferred brighter conditions than the participants in the closed blind conditions. They experienced less visual strain than the participants in the closed blind conditions. The participant's preference for brighter conditions when the blinds were retracted is a somewhat unexpected result. However, there is evidence in academic research that brighter conditions are always preferred unless glare is experienced, particularly when it is provided by natural daylight (Alimoglu and Donmez, 2005; Boubekri et al., 2014; Viola et al., 2008). Additionally, the difference between the mean responses was small ($M\Delta = 0.37$). Experiences of visual strain are frequently caused by glare issues, light flickering, and uneven distributions of light (Boyce, 2014; Viola et al., 2008), therefore its logical that less visual strain was experienced when the blinds were closed than when extended. Shading products not only reduce the level of light entering buildings but also the variations in daylight entering a building. The interrelationship between the lighting sensation, visual strain, and glare is further explored in Section 4.5.5.2.2 (p. 262).

4.5.4.4 Subjective Comfort and Subjective Productivity

When the participants were asked to assess their overall comfort, there were no significant differences in the distribution of the responses or when each participants' mean response were compared between the blind open and blind closed conditions. This suggests that the position of the blinds did not cause a difference in the participants' overall feeling of comfort. Considering that no matter the position of the blinds (open or closed) there are suggested to be positive and negative benefits associated with their position, it is not surprising that a null hypothesis was reached (Wouter et al., 2010). For example, when the blinds are open, they can increase the access to daylight and views out but consequently, some of the occupants may experience glare issues or start feeling too warm if they are located close to the window. The previous research suggests that the façade should be able to adapt dynamically to the changing external weather conditions and the changing position of the sun (Hinge, 2010; Konstantoglou and Tsangrassoulis, 2016). As the study design required the participants to be within conditions that had fixed window and blind positions, it was unlikely that the intervention positions would provide consistent comfortable conditions for all participants. These results are also supported by the internal environmental conditions data that was collected. This suggests that there was no one test day where all of the internal environment conditions remained within the comfort threshold.

When the subjective productivity measures were assessed, a significant difference in the distribution of responses for one of the three measures was found. When the participants were asked whether they believed that the environment was affecting their productivity, χ^2 $(3, N = 179) = 56.49$, $p < .001$ the distribution of responses identified that the participants in open blind conditions felt that the environment was affecting them more. These results are presented in Figure 94. Unfortunately, there was a lack of polarity in the question posed so we are unable to ascertain whether this implied that they thought that the environment was affecting them either positively or negatively.

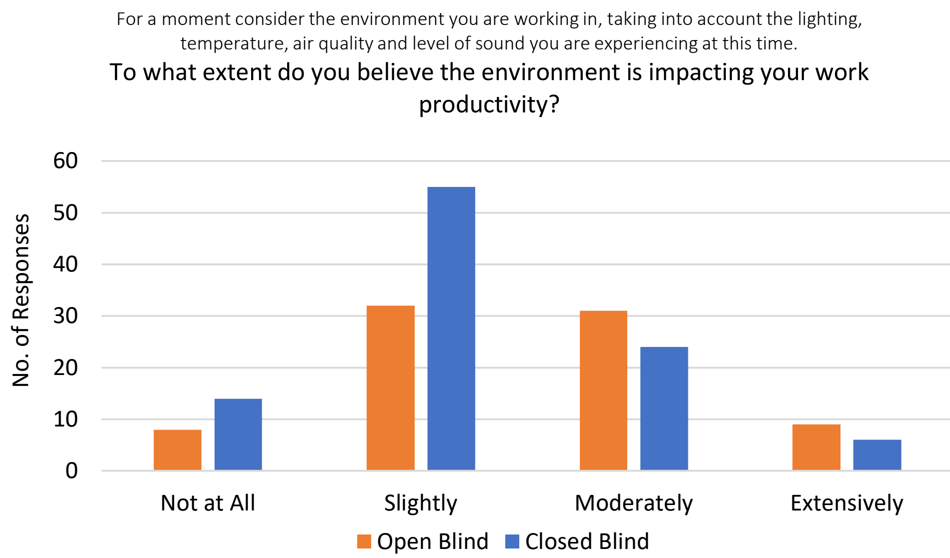

Figure 94. Belief of the environment affecting occupant productivity between open (N = 80) and closed blind (N = 97) conditions.

The paired t-Test results for the subjective productivity measures are presented in Table 41. Two of the three measures used to assess subjective productivity significantly differed. The t-Test results support the results of the χ^2 as they also suggest that the participants in the open blind conditions believed that their productivity was being affected more than it was in the closed blind conditions.

Table 41.Paired t-Test results of the Subjective Productivity Measures (N=19)

Measure	Closed Blind Mean *(SD)*	Open Blind Mean *(SD)*	t	df	Sig. (2-tailed)
Belief of the environment affecting their work productivity	1.21 *0.44*	1.54 *0.53*	3.05	18	0.01**
Presence of external issues that could be affecting their work productivity	2.34 *0.55*	2.47 *0.49*	1.29	18	0.21
Willingness to exert effort on the tasks set	3.32 *0.72*	3.66 *0.82*	2.31	18	0.03*

* $p < 0.05$ ** $p < 0.01$

A significant result was also found when the participants' willingness to exert effort on the tasks set was assessed. The direction of the means suggests that the participants in the open blind conditions reported that they were more willing to exert effort than the participants in the closed blind conditions. The previous research suggests that an increased access to daylight can make occupants feel more alert and less fatigued, having a general positive impact on an occupants' health and well-being (Shishegar and Boubekri, 2016; Viola et al., 2008). The results here suggest that the opening of the blinds affected the individuals positively in terms of their motivation to complete the test battery.

4.5.4.5 Health and Well-being

There were no significant differences between either the distribution of the responses or the mean responses for the health and well-being questions. The lack of significance suggests that there was not a robust difference between the conditions. Potentially, this was a result of the small differences in all the environmental conditions experienced with exception of illuminance. The variation in perceptions of the high illuminance levels experienced in the open blind conditions may have also contributed to a lack of difference in the health and well-being perceptions.

4.5.4.6 Objective Productivity

<u>Work Type Tests</u>

Only one of the three work type tests identified that there was a significant difference in the way that the participants performed between the conditions. The results of all of the tests are presented in Table 42. A significant difference ($p < 0.05$) was found between the participants' text typing speed in the open and closed blind conditions. The participants in the open blind conditions typed more words per minute than the participants in the closed blind conditions. The difference between the mean scores between the open and closed blind conditions identified that the participants in the open blind conditions typed 1.44 more words per minute, which is an overall improvement of 3% in text typing speed.

Table 42. Paired t-Test results of the Work Type Tests (N=19)

Measure	Closed Blind Mean (SD)	Open Blind Mean (SD)	t	df	Sig. (2-tailed)
TEXT TYPING - *No. of Words per Minute*	43.80 (*10.80*)	45.24 (*10.16*)	2.32	18	0.03*
TEXT TYPING - *No. of Errors Made*	2.47 (*1.68*)	2.46 (*1.42*)	0.06	18	0.95
TEXT TYPING - *Accuracy (%)*	94.36 (*3.44*)	94.73 (*2.85*)	0.64	18	0.53
DATA CHECKING - *No. of Questions Answered*	12.00 (*1.92*)	11.63 (*1.88*)	0.65	18	0.53
DATA CHECKING - *No. of Correct Answers*	8.41 (*2.34*)	7.80 (*2.31*)	1.07	18	0.30
DATA CHECKING - *Accuracy (%)*	69.66 (*15.22*)	66.64 (*15.26*)	0.79	18	0.44
GRAMMAR – *No. of Correct Answers*	79.60 (*6.82*)	77.94 (*8.35*)	0.91	18	0.37

* $p < 0.05$

Cognitive Function Tests

Table 43 presents the results of all of the cognitive function tests and measures. Only one of the six tests identified a significant difference in performance. The participants' processing accuracy improved when identifying the control stimuli in closed blind conditions. The difference in the mean performance suggests that there was a 1% improvement in processing accuracy in the closed blind conditions.

Table 43. Paired t-Test results of the Cognitive Function Tests (N=19)

Measure	Closed Blind Mean *(SD)*	Open Blind Mean *(SD)*	t	df	Sig. (2-tailed)
NUMBER SEARCH - *Time Taken (s)*	15.51 *3.04*	15.46 *3.51*	0.08	18	0.94
NUMBER SEARCH - *Accuracy (%)*	0.86 *0.21*	0.76 *0.30*	1.40	18	0.18
REACTION TIME – *Mean Time to give Correct Responses (s)*	0.55 *0.10*	0.55 *0.06*	0.10	18	0.92
REACTION TIME - *Mean Time to give Incorrect Responses (s)*	0.22 *0.14*	0.18 *0.13*	0.97	18	0.35
REACTION TIME - *Mean Time to give All Responses (s)*	0.55 *0.09*	0.57 *0.09*	0.86	18	0.40
PROCESSING SPEED (STROOP) - *Mean Time to respond to Control Stimuli (s)*	0.89 *0.17*	0.93 *0.15*	1.44	18	0.17
PROCESSING SPEED (STROOP) - *Mean Time to respond to Incongruent Stimuli (s)*	1.12 *0.27*	1.15 *0.21*	1.08	18	0.29
PROCESSING SPEED (STROOP) - *Mean Time to respond to Congruent Stimuli (s)*	0.90 *0.17*	0.93 *0.18*	1.34	18	0.20
PROCESSING ACCURACY (STROOP) - *Accuracy of responses to Control Stimuli (%)*	99.00 *0.99*	98.19 *1.66*	2.37	18	0.03*
PROCESSING ACCURACY (STROOP) - *Accuracy of responses to Incongruent Stimuli (%)*	89.65 *17.90*	88.05 *25.44*	0.67	18	0.51
PROCESSING ACCURACY (STROOP) - *Accuracy of responses to Congruent Stimuli (%)*	98.46 *1.65*	97.90 *1.95*	1.61	18	0.13
SHORT TERM MEMORY - *No. of Correct Responses*	0.57 *0.27*	0.49 *0.31*	0.92	18	0.37
WORKING MEMORY – *No. of digits recalled correctly*	6.15 *2.93*	6.67 *3.15*	1.82	18	0.09
LONG TERM MEMORY – *No. of correct answers*	5.25 *1.65*	5.33 *1.66*	0.61	18	0.55

* $p < 0.05$

4.5.5 Cross Analysis of the Individuals Responses between the Open and Closed Blind Positions

4.5.5.1 Perceptions of Sensation, Preference, and Acceptability

The research suggests that perception and consequently the preferences and acceptability of the environment varies from individual to individual. Therefore, in this section, the participants' sensations, preferences, and acceptance of the differing environmental conditions have been reviewed. This section presents each of the participant's response to the measures and analyses them to determine whether all of the participants responded in a similar way when the blinds were either open or closed.

4.5.5.1.1 Thermal Comfort

Figure 95. displays the Min, Max, and Mean response of each individual participant for the three thermal comfort measures. The mean responses show that not all of the participants responded in the same way when they were in either condition. Fourteen of the nineteen participants' mean responses suggested that the air temperature felt warmer in the open blind conditions than in the closed blind conditions. Their mean responses shifted by between 0.05 (Participant A115) to 2.00-pts (Participant A106) on the thermal sensation scale. Four of the remaining five participants suggested that the air temperatures felt cooler in the open blind conditions than in the closed blind conditions (Participants A111, B106, B111, B112). However, the mean shift in these responses was much smaller and ranged between 0.11 - 0.33-pts (Participant A111 and B112). The last remaining participant identified that the air temperature felt the same in either condition (Participant A104).

Similarly, differences were found in the way that the participants responded to how they would prefer the air temperature to be and how acceptable the air temperatures were. Most of the participants suggested that they would prefer it to be cooler (nine out of the nineteen) and that the air temperature was more unacceptable (ten out of the nineteen) in the open blind conditions. However, four of the participants identified that they would prefer the air temperature to be cooler in the closed blind conditions and six of the participants suggested that it was more unacceptable when the blinds were closed. The remaining participants (six out of the nineteen) suggested that they would prefer it to be equally cooler in both blind closed and blind open conditions and that both blind open and blind closed conditions were equally acceptable (three out of the nineteen).

When comparing the responses between the three questions, six of the participants responded in a similar way (A102, A106, A108, A115, B107, and B114). Their mean responses all identified that in the open blind conditions, they felt warmer, that they preferred it to be cooler, and that they identified that the air temperatures were less acceptable than in the closed blind conditions. The way in which the rest of the participants responded to the three questions differed and all of the other patterns of responses were only common among a maximum of three participants. Considering that less than half of the participants responded in a logical way (i.e., when they reported it was hot, they preferred cooler conditions and when they felt that the air temperatures were more unacceptable), it suggests that other factors (i.e., other than the air temperature) influenced their responses to the questions.

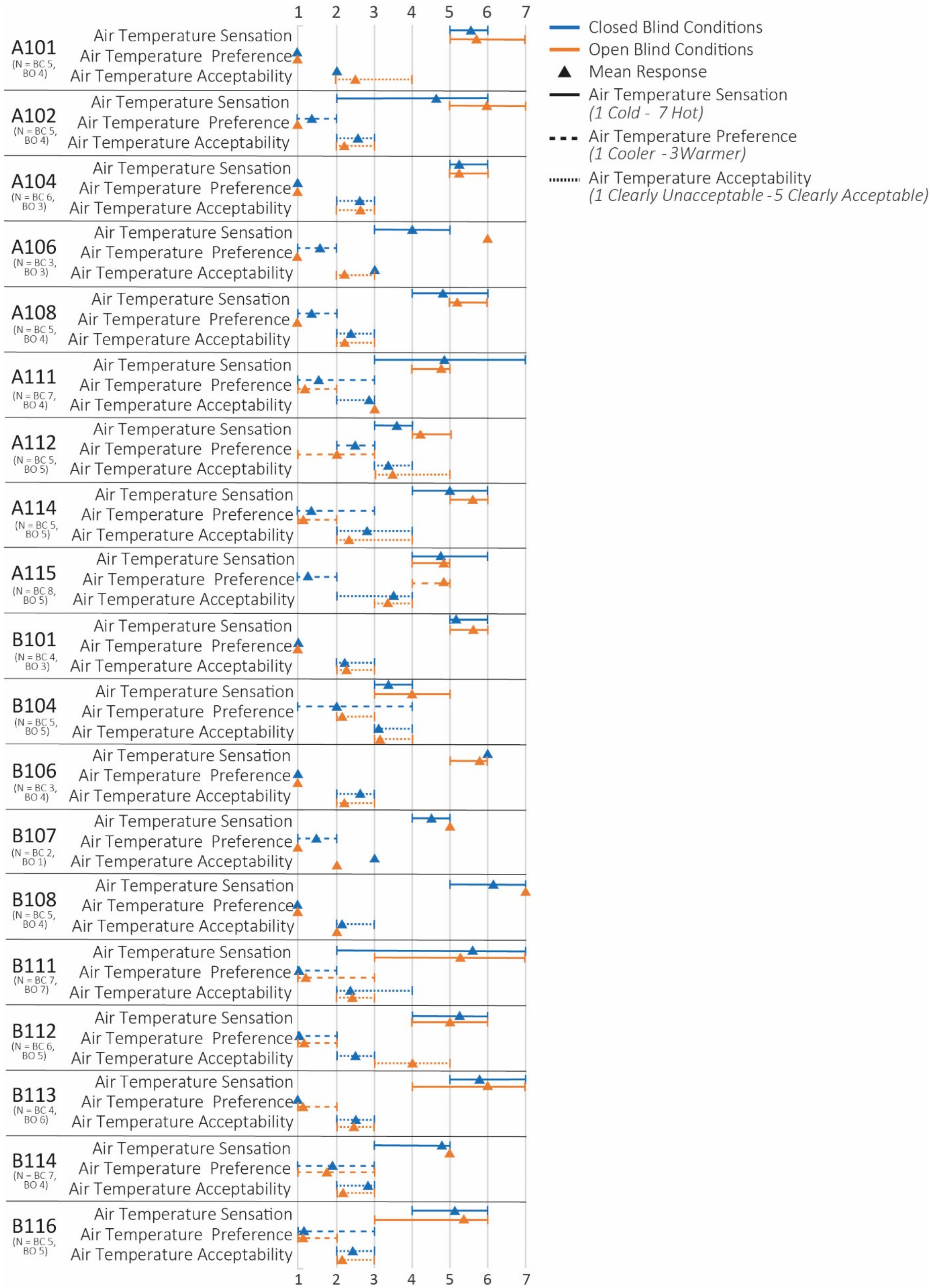

Figure 95. Air Temperature Sensation, Preferences and Accepability between the participants in the open and closed blind conditions (BC = Blind Closed, BO = Blind Open).

4.5.5.1.2 Air Quality

Figure 96 displays the Min, Max, and Mean response of each individual participant for the six air quality measures. More than two thirds of the participants' mean responses suggested that the air felt less fresh in the open blind conditions. The remaining five participants' mean responses suggested that the air was fresher when the blinds were open (Participants A112, B104, B111, B112, and B113). Just over one third of the participants mean responses suggested that when the blinds were open, they had a greater preference for fresher air and a further third of the participants suggested that they would prefer to have fresher air in both the open and closed blinds conditions. The remaining five participants suggested that they would prefer the conditions to be fresher when the blinds were closed (Participants A111, A112, B108, B111, and B112).

When comparing the responses between the air freshness sensation and preferences, six of the participants responded in a similar way (A102, A104, A108, A115, B101, B106, and B116). Their mean responses all identified that the air was fresher when the blind was closed. However, their preference for fresher conditions did not differ depending on the blind position. The way in which the rest of the participants responded to the two questions differed and all other patterns of responses were only common among a maximum of three participants.

Most of the participants (eleven out of nineteen) suggested that the air was more humid when the blinds were open. Four participants identified that it was less humid when the blinds were open, and a further four participants suggested that there was no difference between the perceptions of humidity in either condition. Over a third of the participants (seven out of nineteen) had a mean response that identified that blind position did not affect how they preferred the level of humidity to be. A further seven participants suggested that they would prefer the conditions to be drier when the blinds were open, and five participants preferred the air to be more humid when the blinds were open.

When comparing the responses between air humidity sensation and preferences, five of the participants responded in a similar way (A102, A106, A112, B114 and B116). Their mean responses all identified that it was more humid in the open blind conditions, and that they would prefer it to be drier. A further four participants (A101, A104, A106, and B106) also responded in a similar way and suggested that they did not have a differing preference between the blind open or closed conditions. They felt that the air was more humid when the blinds were open. The way in which the rest of the participants responded to the two questions differed and all other patterns among the responses were only common among a maximum of two participants.

Lastly, the participants' perceptions of their odour/fragrance sensation were evenly split between the conditions. Seven participants suggested that the fragrance was more pleasant when the blinds were open, and seven participants suggested that the fragrance was more pleasant when the blinds were closed. The remaining five participants' mean responses suggested that there were no differences between the two conditions. There was also little difference in the way that the participants responded in terms of how they would prefer the odours or fragrances to be in the office. Eight participants suggested that they would prefer less pleasant odours when the blinds were open, and six participants suggested that they would prefer more pleasant odours or fragrances when the blinds were closed. Five of the participants suggested that there was no difference between the conditions.

When comparing the responses between air odour sensation and air odour preference, five of the participants responded in a similar way (A104, A112, A108, A111, and B112). Their mean responses all identified that the air odours were more pleasant when the blinds were open as opposed to when they were closed. They prefer them to be less pleasant than in closed blind conditions. The way in which the rest of the participants responded to the two questions differed and all other patterns in the responses were only common among a maximum of three participants.

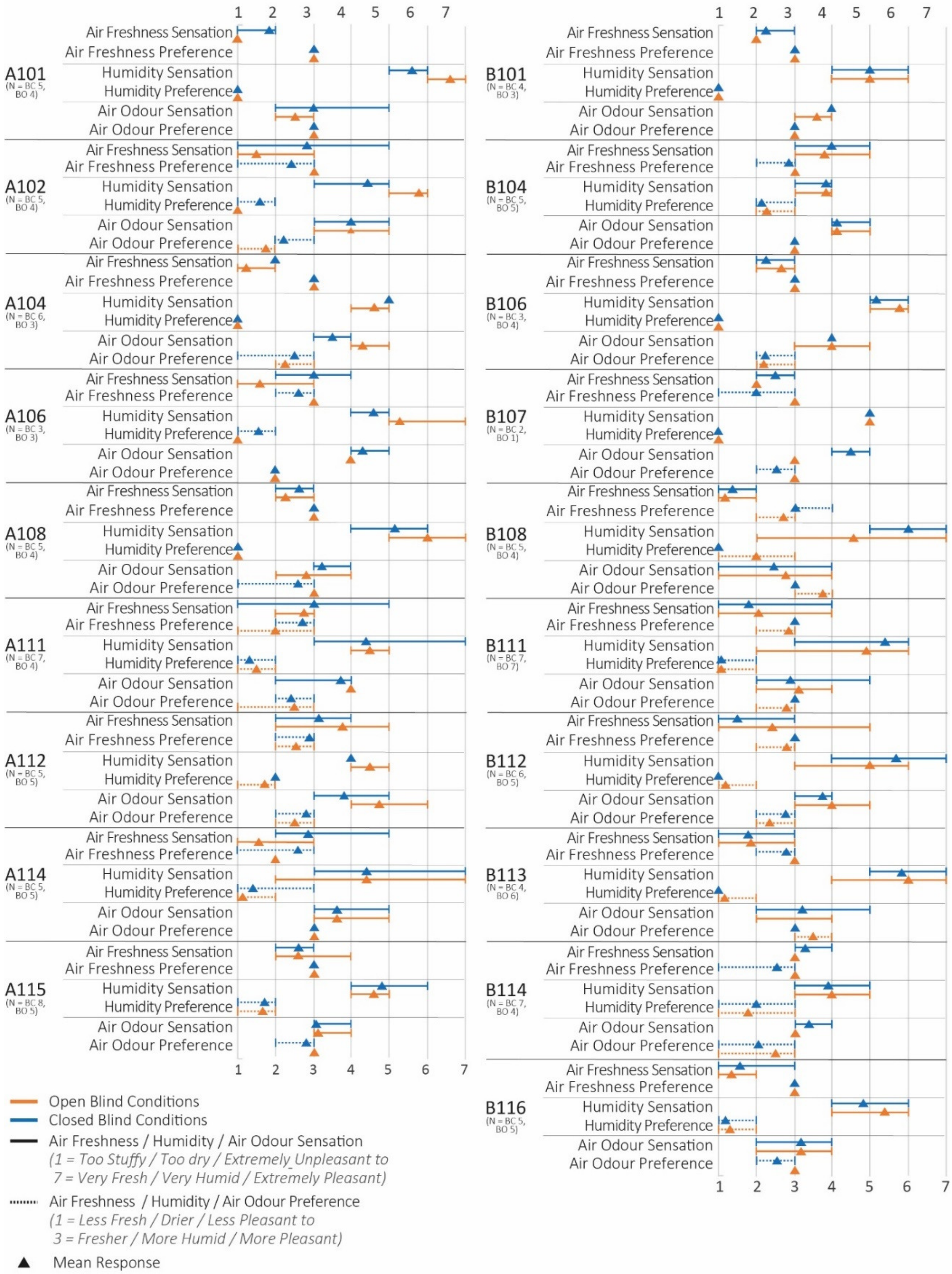

Figure 96. Air Freshness, Humidity and Air Odour Sensation and Air Freshness, Humidity and Air Odour Preferences between the participants in both the open and closed blind conditions (BC = Blind Closed, BO = Blind Open).

4.5.5.1.3 Visual Comfort

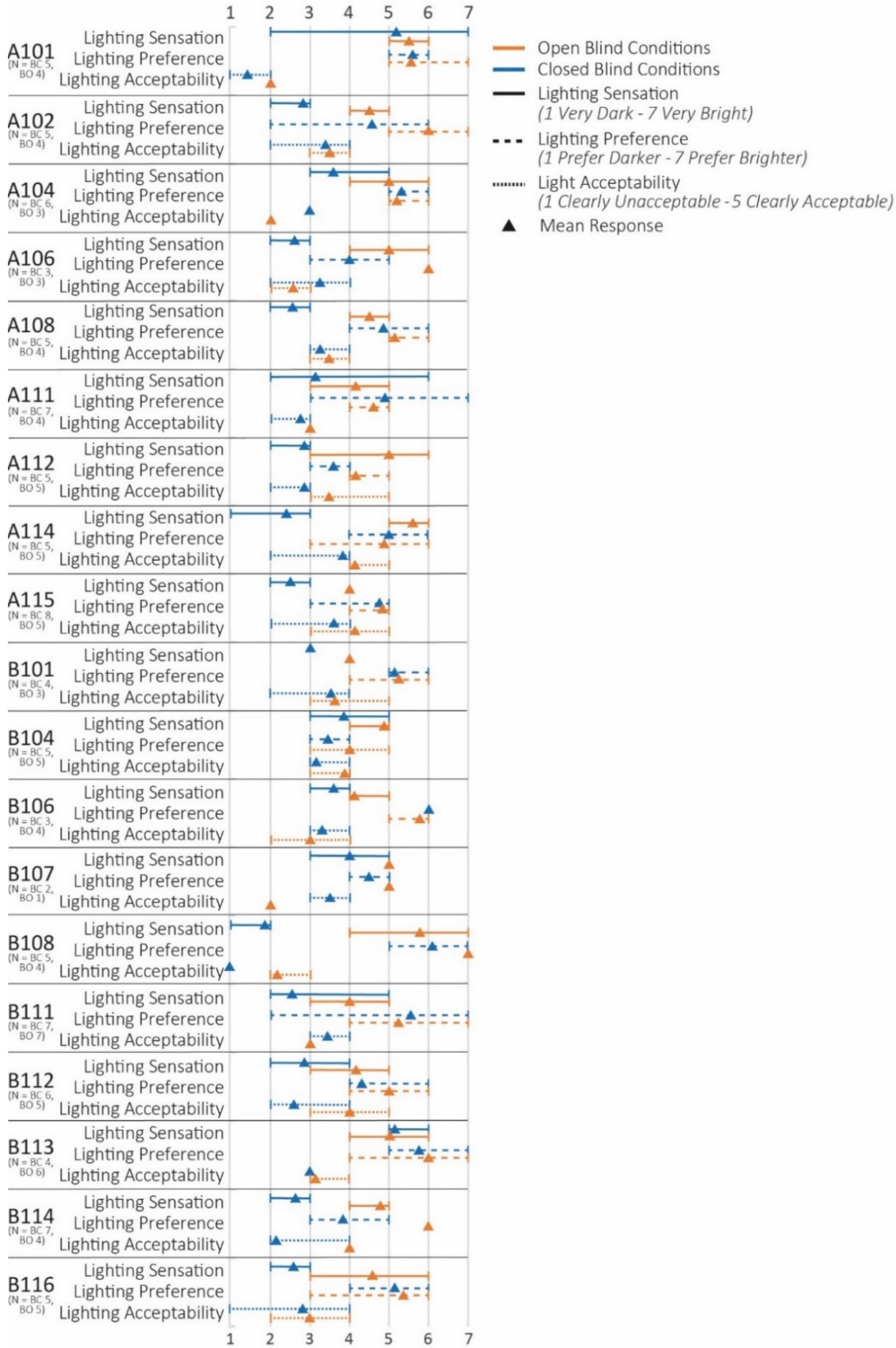

Figure 97. Lighting Sensation, Preferences and Acceptability between the participants in both the open and closed blind conditions (BC = Blind Closed, BO = Blind Open).

Figure 97 displays the Min, Max, and Mean response of each individual participant for three of the ten visual comfort measures. Eighteen of the nineteen participants perceived the conditions to be brighter when the blinds were open. Their mean responses shifted by between 0.05-pt (Participant A101) and 3.95-pts (Participant B108) on the lighting sensation scale. Only one participant's mean response, (Participant B113) showed that they experienced brighter conditions when the blinds were closed as opposed to open with a mean difference of 0.25-pts.

The participants' responses to how they would prefer the level of brightness and how acceptable the level of light was were more variable between the individual participants. Most of the participants (thirteen out of the nineteen) suggested that they would prefer for it to be even brighter when the blinds were open. Five participants identified that they would prefer the light levels to be brighter when the blinds were closed, and one participant suggested that they would prefer it to be equally brighter in both the blinds closed and blinds open conditions. Most of the participants (fifteen out of the nineteen) also reported that the level of brightness was more acceptable in the open blind conditions, and the remaining four participants suggested that it was less acceptable when the blinds were closed.

When comparing the responses between the three variables, just over half of the participants (ten out of the nineteen) responded in a similar way. Their mean responses all identified that in the open blind conditions, it was brighter. They preferred it to be even brighter, and they identified that the level of brightness was more acceptable than the closed blind conditions. The way in which the rest of the participants responded to the three questions differed and all other patterns of responses were only common among a maximum of three participants. This is an interesting result as it suggests that overall, the participants prefer further brighter conditions even when the conditions are perceived to be bright and considered acceptable. Potentially this is dependent on the type of light that is provided. For example, if higher illuminance levels were provided by electric lighting, the participants may not necessarily prefer brighter conditions. In this study, the changes in illuminance were provided by daylight as electric lighting was consistently in use on all test days.

4.5.5.1.4 Summary

There was a large amount of variability in the way that the individuals responded to the three related measures (i.e., sensation, preference, and acceptability) for each environment quality measure assessed. However, overall, a large proportion of the participants responded to the questions in a similar way. Upon reflection of the study design and the overall warm conditions that were present in both open and closed blind conditions, it is unsurprising that there was variation in the way that the participants responded between the three related measures (i.e., sensation, preference, and acceptability) in relation to thermal comfort. Firstly, the study design was unable to control for all factors that influence a person's sensation. For example, between the test days, it is likely that the participants' clothing level, food and drink intake, and activity level (or the amount of time they had been at their desk prior to the test) differed compared to the other days, which could have influenced their responses. Additionally, a person's physiological response differs according to individual factors such as age, gender, ethnicity, and health condition, all of which can affect how sensitive individuals are to changes in the environmental condition. Even though some of this type of data was collected (i.e., age, gender, the duration of time at the desk prior to the test, and clothing level), splitting the data into these additional variables meant that the data set was too small to identify any meaningful relationships. Interestingly, the participants' responses to the visual comfort questions were more consistent. This may be because they were exposed to very contrasting environments between the conditions, whereas the other participants were exposed to less contrasting air temperatures and air quality conditions.

4.5.5.2 Further Relationships found between the Measures and the Open and Closed Blind Conditions

Spearman's Rho correlation[40] was used to identify the relationships between the measures and between all participants in either the blind open or blind closed conditions. An individual analysis of the participants was not feasible due to the small number of responses from each participant in either the blind open or blind closed conditions. Due to the large number of measures considered, only the interesting relationships found have been selected and discussed here.

4.5.5.2.1 Objective Air Temperature and Air Temperature Sensation

When analysing the full dataset, the participants' perception of the air temperature and the objective mean air temperature data were found to be positively correlated ($r_s = 0.43$, $p < 0.01$). When grouped by the blind condition and analysed, they were also positively correlated (blind open, $r_s = 0.36$, $p < 0.01$, and blind closed $r_s = 0.45$, $p < 0.01$). These relationships have been presented in the scatter plot in Figure 98. The mean air temperature is presented on the Y-axis and the participants' air temperature sensation

[40] See the explanation for Spearman's Rho Correlation in Section 4.5.2 (p. 183) Relationship Between Blind Position and the Internal Objective Environment Measures.

response is plotted on the X-axis. Figure 98 identifies that as the temperature increased in both conditions, as a group, the participants appropriately identified feeling warmer. Figure 98 also identifies that the participants related a broad range of temperatures to a specific air temperature sensation response. For example, when the participants perceived the air temperature as 'Neutral' (4 on the X-axis), the mean air temperatures ranged between 22.3 and 27.7°C.

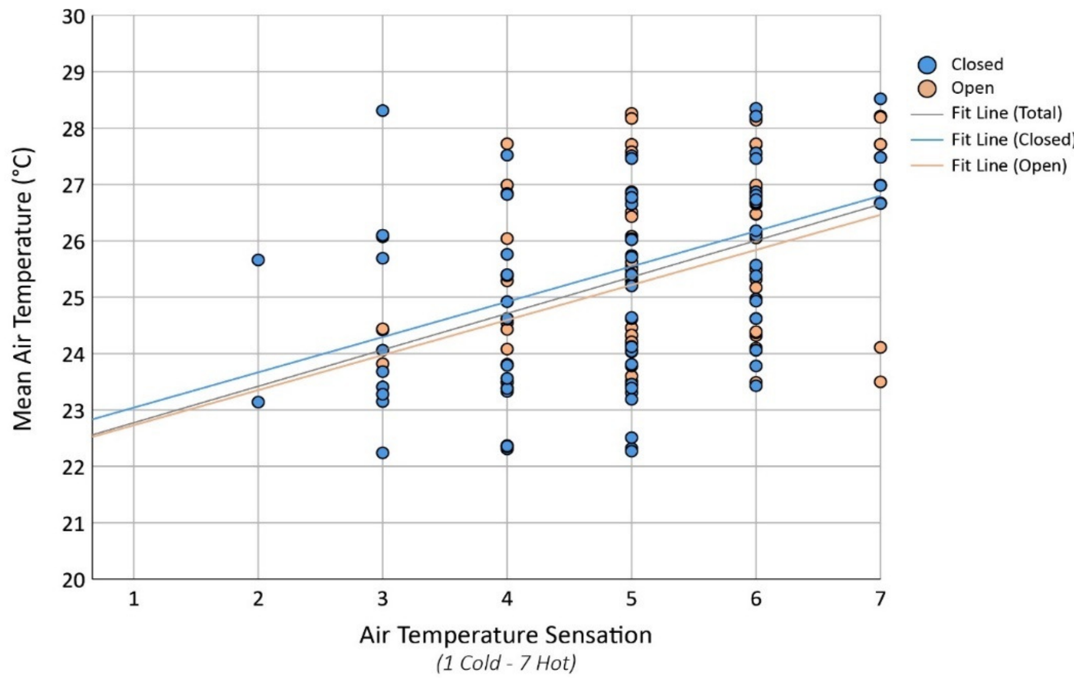

Figure 98. Mean Air Temperature (°C) and Air Temperature Sensation responses in the blind closed (●) and blind open (●) conditions (Blind Closed = 97, Blind Open N = 80) with lines of best fit.

Figure 99 presents each participants' thermal sensation responses in relation to the mean air temperature measured. The left scatter plot shows the participant's responses in the open blind conditions and the right scatter shows the closed blind responses. It can be observed that each participant's set of responses did not always correlate with the mean air temperature. For example, Participant B104 in the open blind conditions reported feeling 'Neutral' at 27°C but in the same condition, they also reported feeling 'Warm' at 26°C. It can also be observed that there were differences in how sensitive the participants were to the changes in air temperature. For example, Participant B104 suggested that the conditions were 'Neutral' when the temperatures ranged from 26.8°C to 27.7°C where Participant A104 perceived it to be 'Neutral' at 22.3°C. This identifies that there was a 4.5°C difference between the participant's perceived 'Neutral' air temperature sensation responses.

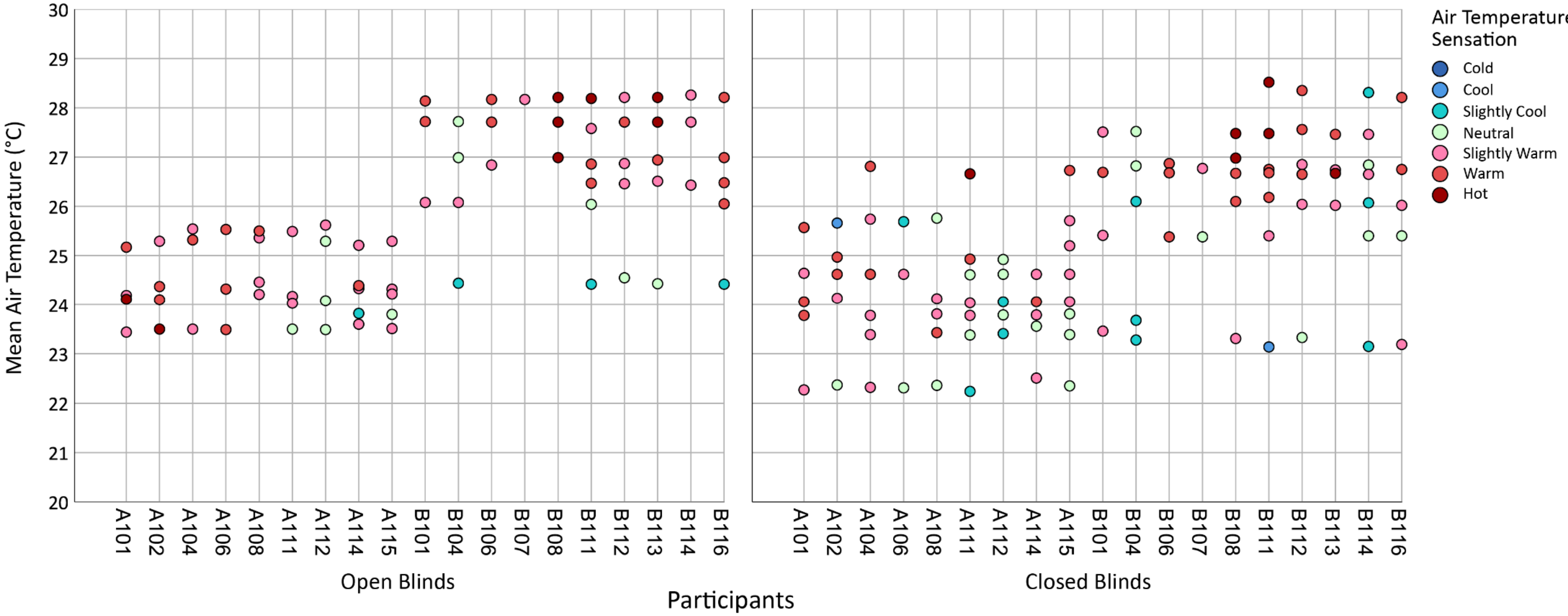

Figure 99. Mean Air Temperature (°C) and Air Temperature Sensation response in the open and closed blind conditions for each participant (Open Blind N = 80, Closed Blind N = 97)

4.5.5.2.2 Objective Illuminance and Lighting Sensation, Visual Strain, and Identifiable Glare Issues

Objective Illuminance and Lighting Sensation

The participants' perception of the lighting and the mean internal illuminance ($r_s = 0.56$, $p < 0.01$) were positively correlated upon assessing all of the participants' responses. This relationship is presented in Figure 100 with the mean illuminance level on the Y-axis and the light sensation response on the X-axis. The linear line of best fit identifies the difference in relationships when assessing all responses (N = 171) and the responses provided in the blind open (N = 80) and blind closed conditions (N = 97). There was a non-significant correlation between the mean internal illuminance and the participant's light sensation responses when the participant's responses were grouped by blind position.

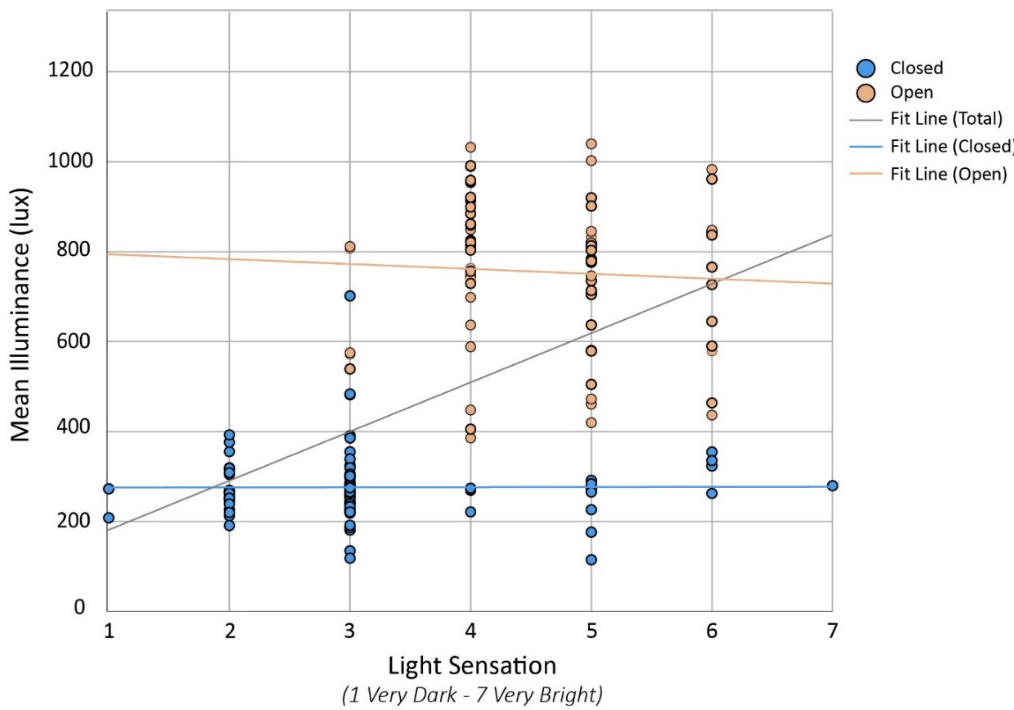

Figure 100. Relationship between mean illuminance (lux) and light sensation responses in the blind closed (●) and blind open (●) conditions (blind closed = 97, blind open N = 80) with lines of best fit.

This suggests that when the data was split between the blind positions, there was an increased amount of variance within the smaller groups of data. Two reasons may explain why there was an increased amount of variance in the data. Firstly, the glare issues perceived by participants may have resulted in a greater brightness response being reported where the mean illuminance data would not have been able to account for the level of light experienced at eye level at that precise moment in time. Secondly, cloud cover in the open blind condition may have resulted in a slightly darker perception of the lighting where the mean illuminance may have reflected a high illuminance as it was average for the 30 - 45-minute period that the participants answered the tests and questions within.

The mean illuminance metric in this study was only representative of the light levels on the horizontal plane in the task area. It was the mean value for the duration of time each participant answered the questionnaire. Therefore, the mean illuminance was not able to accurately identify the level of light perceived by each occupant at the specific moment that they responded to the light sensation question. Even though average spot measurements are useful to determine the average light levels experienced, they can only provide an indication of the light levels being experienced by an occupant. Internal illuminance is highly variable when daylight contributes to the light internally. However, it is generally thought that closing the blinds can help reduce this variability.

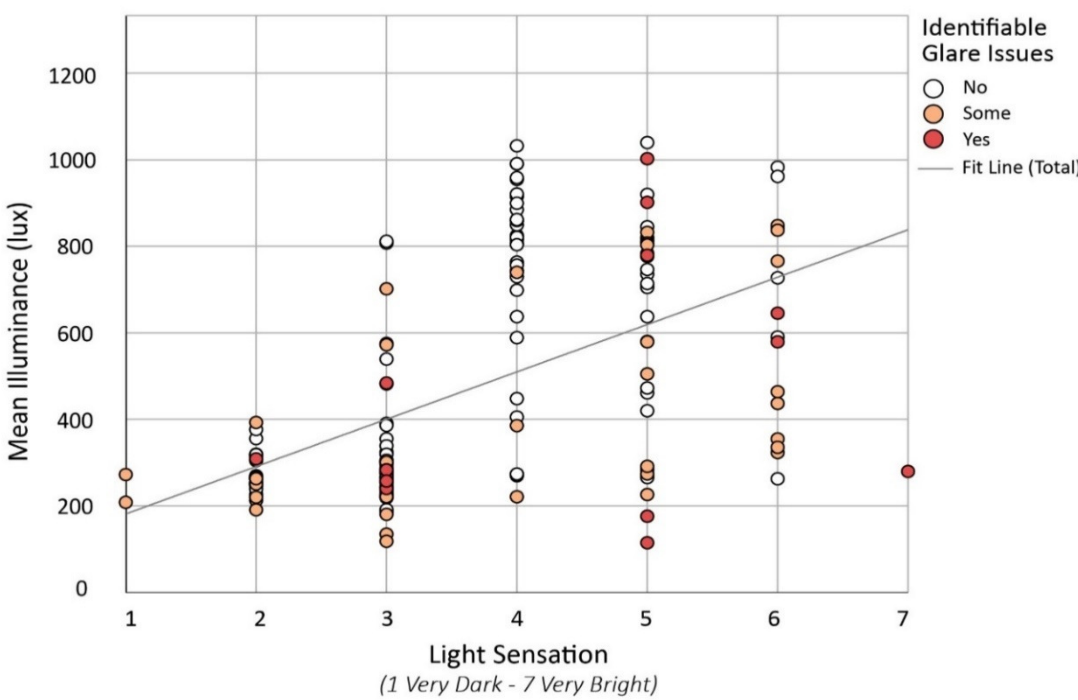

Figure 101. Relationship between mean illuminance (lux), light sensation, and identifiable glare issues with the line of best fit (N = 171).

Figure 101 presents the same data in Figure 100 but each data point has been colour coded to identify the participants that reported a glare issue. It can be observed that removing the participants that identified ‘Yes’ or ‘Some’ glare issues would reduce the scatter in the data. The data was reanalysed without those participants that responded ‘Yes’ or ‘Some’ to the glare issue question. However, a null hypothesis was still reached between the light sensation and mean illuminance in both the blind open and closed conditions. This suggests that it was not glare alone that created the variance in the data and that the factors discussed above (i.e., cloud cover and the average metric used to determine illuminance) created variance.

Figure 101 also identified that some participants experienced glare issues when they perceived the lighting conditions as either bright or dark. Upon review of the data generally, when the blinds were closed, the majority of glare issues occurred when participants perceived the conditions as dark and when the blinds were open, glare issues were reported when the participants perceived the conditions as bright. These differences suggest that the glare experienced was caused by different factors in the open and closed blind conditions, specifically the poor distribution of light in closed blind conditions and too high of an illuminance in open blind conditions.

Figure 102 presents each participants' lighting sensation response in relation to the illuminance measured during the test sessions. The left scatter indicates the participants' responses in open blind conditions and the right scatter shows the closed blind responses. Like air temperature, it can be observed that an individual's perception of the lighting conditions does not always correlate with the objective illuminance measure. For example, Participant B108 in the open blind condition reported that illuminance levels close to 800 lux were perceived as both 'Neutral' and 'Bright'. It can also be observed that there were differences in how sensitive the participants were to the changes in illuminance. These also differed depending on whether the blinds were opened or closed. Interestingly, when reviewing a specific response type between the conditions, there is a significant difference between the illuminance levels related to these responses. For example, when the blinds were closed, several participants identified that the internal conditions were 'Neutral' when the mean illuminance was low (between 200 - 300 lux). However, the same participants in open blind conditions suggested that a neutral lighting sensation response was related to a mean illuminance > 400 lux. This shift in perception between individuals may be related to the participants' expectations of the lighting conditions. When the blinds are closed, they expect the lighting conditions to be darker, therefore there is a shift in their sensation in relation to the mean illuminance level depending on the position of the blind.

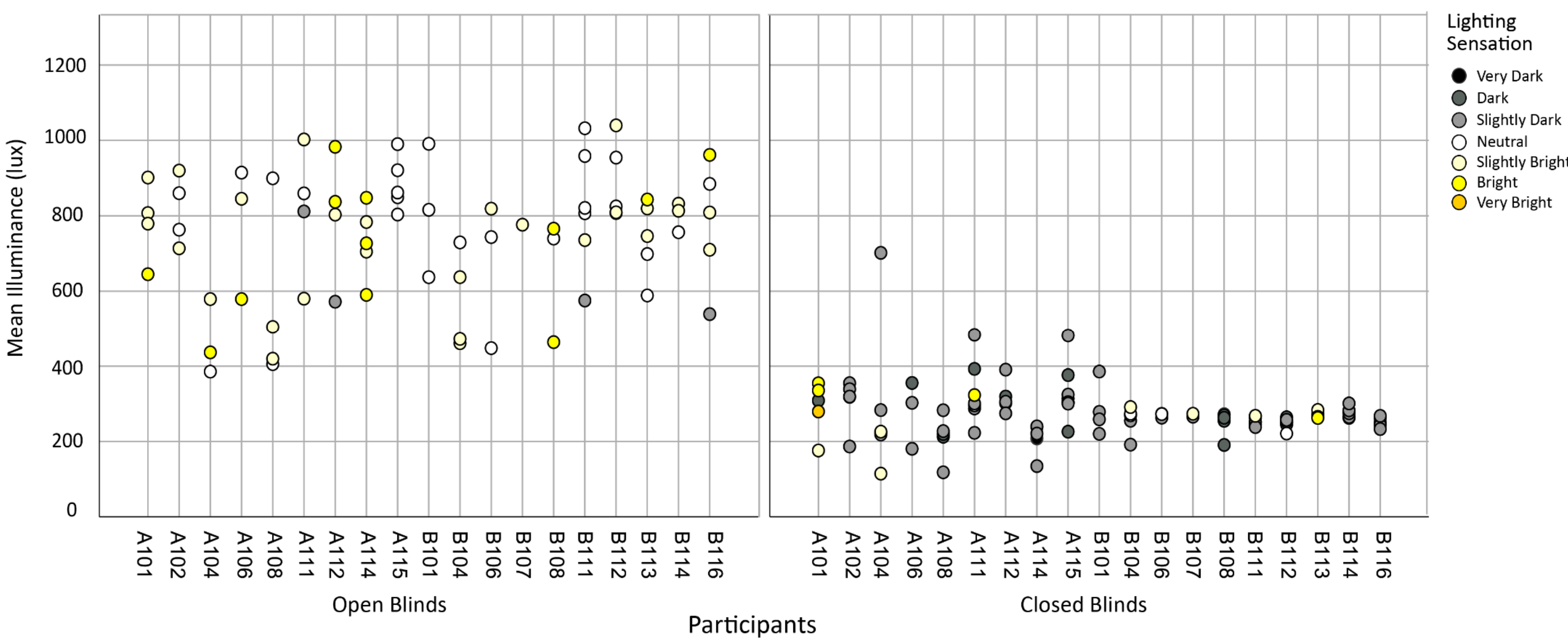

Figure 102. Mean Illuminance (lux) and Lighting Sensation response in both open and closed blind conditions for each participant (Blind Closed N = 97, Blind Open N = 74)

When examining the range of responses in the closed blind conditions in Section 4.5.4.3.4 (p. 242), several participants (A101, A104, A111, B104, B107, B111, and B113) experienced 'Slightly Bright' or brighter conditions when the blinds were closed. In total, there were fourteen instances where this occurred. The fourteen responses were cross-analysed to assess whether the participants had also identified glare issues when providing their light sensation response. This would also help to explain why they reported a brighter sensation of light when the blinds were closed. Figure 103 displays that the participants in the closed blind conditions that reported 'Slightly Bright' or brighter conditions alongside their glare response. This is in addition to the mean illuminance level measured locally to them during the test session.

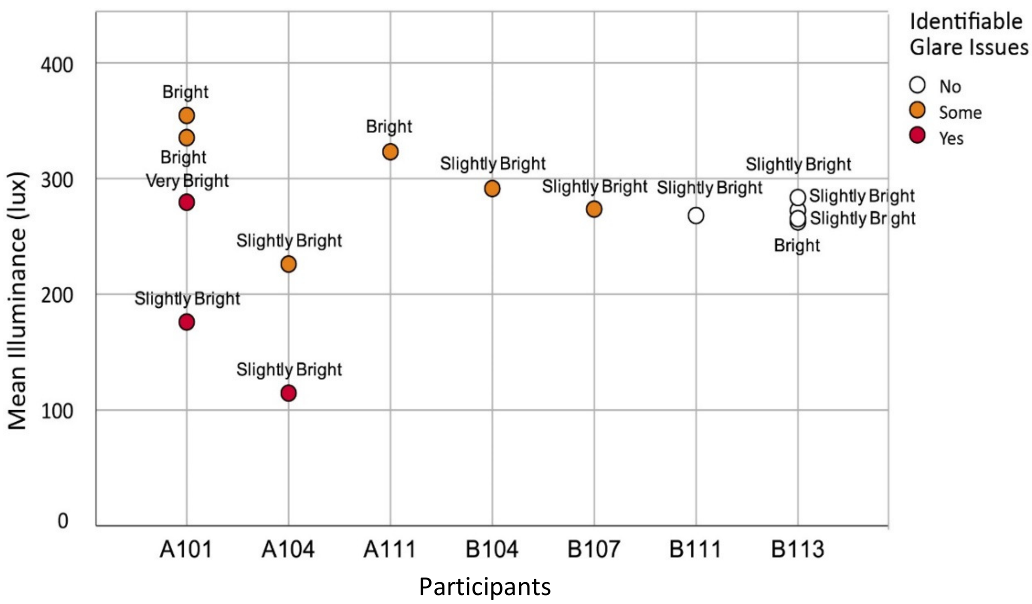

Figure 103. Participants in the Closed Blinds context that reported Slightly Bright, Bright or Very Bright lighting conditions and the mean illuminance (lux) and their Identifiable Glare Issues response.

'Slightly Bright' or a brighter light sensation were reported on nine occasions when glare issues were also identified in the closed blind conditions. However, on five occasions in total, participant B113 and participant B111 identified that there were no glare issues, but they still felt that the light conditions were 'Slightly Bright' or 'Bright'. On these five occasions, the mean illuminance levels were below the comfort threshold (< 300 lux). This suggests that their responses were unrelated to the actual illuminance level measured, meaning that they were not related to a glare issue. These five responses cannot be further explained by the data collected and they are potentially anomalous responses. As previously discussed, they are an indicator showing that the mean illuminance levels measured are not appropriate for identifying at what illuminance level glare issues are experienced.

Lighting Sensation and Visual Strain

Figure 104 displays the relationship between the participants' perception of light brightness and their reported experience of visual strain in both the blind open and blind closed conditions.

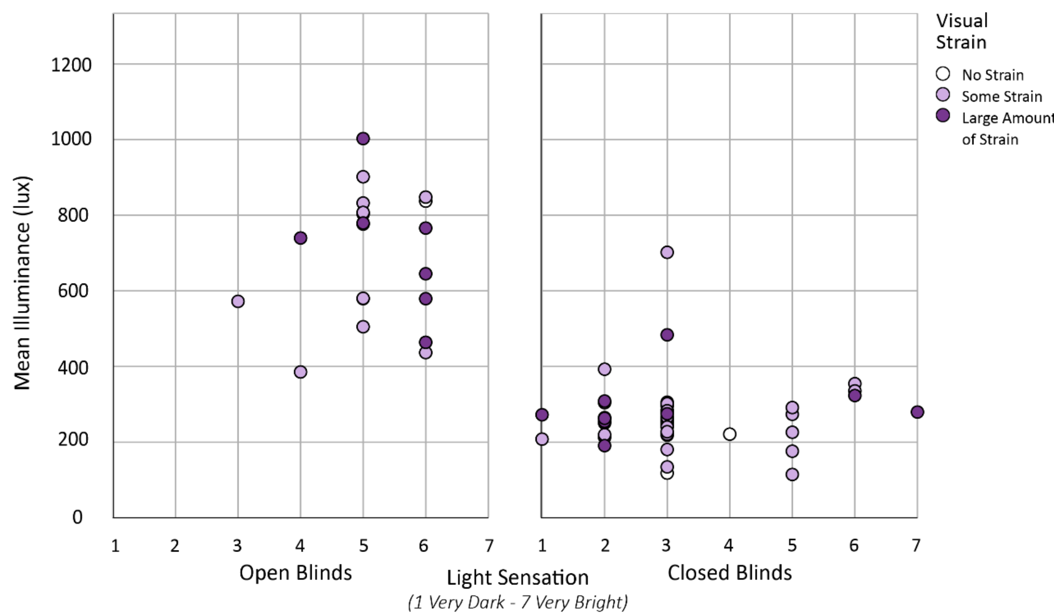

Figure 104. Lighting sensation and visual strain scatter plot of the blind closed (N = 97) and blind open (N = 80) responses.

There was a significant relationship found between the two variables in the blind open conditions ($r_2 = 0.44$, $p < 0.01$). However, in the blind closed conditions, there was no significant relationship found. This suggests that only when the blinds were open did the participants perceive brighter conditions and visual strain. In the blind closed conditions, experiences of visual strain were independent of their perception of brightness. This does not mean that visual strain was not experienced in blind closed conditions. It was not found to be related to the participants' perceptions of brightness.

Glare issues are often identified where there is too great a contrast between the visual task and the surrounding environment. Too harsh a contrast between the illuminance levels around the visual task can result in visual discomfort, resulting in visual strain being experienced (Wouter et al., 2010). To assess whether visual strain was experienced when the blinds were open was solely due to glare issues being experienced, the participants that identified glare were removed from the dataset and the data was re-evaluated. When glare was not experienced in the open blind conditions, the perceptions of brighter lighting conditions were still positively related to visual strain ($r_2 = 0.34$, $p < 0.01$). This suggests that visual strain was experienced in the blind open conditions when the level of light was perceived as brighter regardless of the presence of glare issues.

Light Sensation and Glare

As expected, there was a positive relationship found between the participants' perceptions of brightness in open blind conditions and identifiable glare issues when the blinds were open ($r_2 = 0.41$, $p < 0.01$). This suggests that glare was experienced when the participants perceived brighter lighting conditions when the blinds were open. However, there was no relationship found when the blinds were closed. This is because several participants reported glare issues. They also reported the conditions as 'Slightly Dark', 'Dark' or 'Very Dark', creating variance within the data. This suggests that the participants did not always consider the conditions to be bright when they experienced glare issues. This is interesting as generally glare is only associated with bright perceptions in the environment. Glare issues identified in the perceived darker lighting conditions are likely a result due to the contrast in illuminance levels around the visual task. If the peripheral environment had a low illuminance and their illuminated computer screen produced too stark a contrast, this may have been perceived as a glare issue.

Visual Strain, Glare and Objective Illuminance

As expected, visual strain was positively correlated with identifiable glare issues when the blinds were open ($r_2 = 0.52$, $p < 0.01$) and when the blinds were closed ($r_2 = 0.31$, $p < 0.01$). This suggests that visual strain was experienced when glare was identified in both conditions. In Figure 104 and Figure 105, visual strain and glare issues were identified at varying mean illuminance levels. These illuminance levels varied between the participants. As previously mentioned, mean illuminance is not the appropriate measure to identify the point when glare and visual strain are experienced. This was beyond the scope of the study design to evaluate. However, it can be observed that both glare and visual strain were identified at lower mean illuminance levels within the 300 - 500 lux comfort thresholds on the horizontal plane in both conditions.

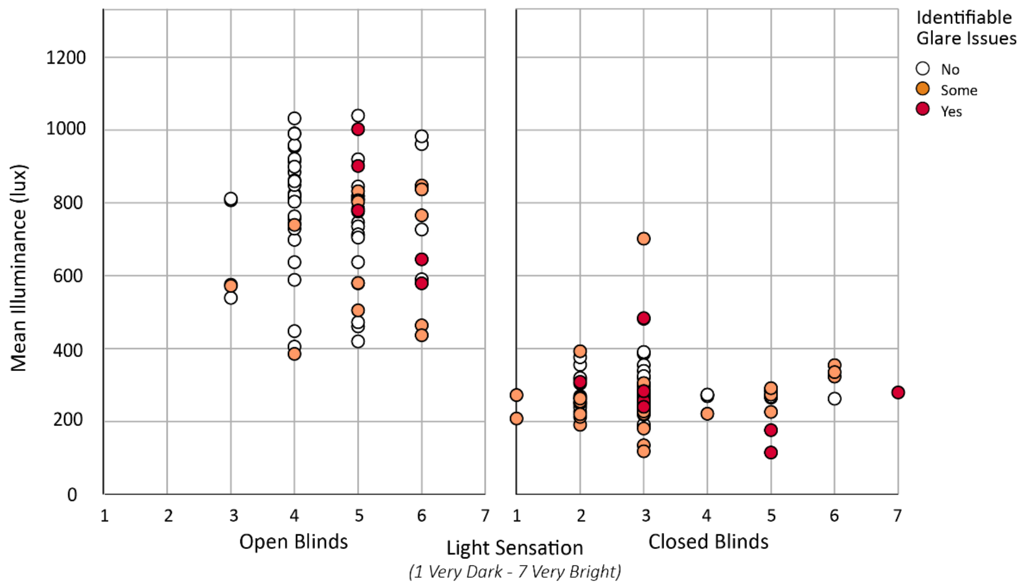

Figure 105. Lighting sensation and identifiable glare issues scatter plot for the blind closed (N = 97) and blind open (N = 80) responses.

4.5.5.2.3 Overall Comfort and Environment Sensation

The participants' perceptions of air temperature, the level of brightness, humidity, air freshness, odours/fragrances, and view were assessed to identify whether these variables have a relationship with their responses to the overall comfort question. The same variables were assessed when the participants were in either closed or open blind conditions to identify whether the different perceptions were related to their overall comfort response. Differences in the significant relationships suggest that the participants' perceptions were more variable in one condition as opposed to the other.

In open blind conditions, the participants reported being more comfortable when they perceived darker conditions (r_2 = -27, $p < 0.05$), cooler air temperatures (r_2 = -0.58, $p <$ 0.01), less humid conditions (r_2 = -0.48, $p < 0.01$), and fresher air (r_2 = 0.60, $p < 0.01$). The relationship found between overall comfort and perceptions of brightness was somewhat expected. While brighter conditions are preferred by the occupants, they can be detrimental to the perceptions of comfort as if it is too high, illuminance can make the occupants feel uncomfortable when they experience glare or visual strain (CIBSE, 2020). This analysis was repeated with all of the participants that reported glare issues being removed from the dataset. Without those who experienced glare being present, the perceptions of brightness were found to be unrelated to occupant comfort.

When the blinds were closed, the cooler perceptions of air temperature (r_2 = -0.43, $p <$ 0.01), less humid conditions (r_2 = 0.42, $p < 0.01$), and a fresher perception of the air (r_2 =

0.39, $p < 0.01$) were similarly related to the overall more comfortable response. However, additionally the participants perceiving more pleasant fragrances ($r_2 = 0.33$, $p < 0.01$) was also found to be related to the participants reporting a more comfortable response. The participants' perception of odours was more variable in open blind conditions than in closed blind conditions. The significance of this result suggests that the psychological effect of pleasant odours is an important factor in office comfort. Interestingly, the perceptions of view and noise were not related to the participants' overall comfort response in either condition, suggesting that the participants' responses were variable.

4.5.5.2.4 Environment Sensation

The participants' perceptions of air temperature, the level of brightness, humidity, air freshness, odours/fragrances, and view were assessed to identify whether these variables have a relationship with one another. The same variables were assessed when the participants were in closed and open blind conditions to identify whether the different perceptions were related to their overall comfort response. As stated previously, the differences in the significant relationships suggest that the participants' perceptions were more variable for one condition as opposed to the other. The relationships for each sensation have been reported below, followed by a discussion of the most interesting results found.

Air Temperature Sensation

In the open blind conditions when the participants perceived warmer air temperatures, they perceived more humid conditions ($r_2 = 0.61$, $p < 0.01$), less fresh air ($r_2 = -0.69$, $p < 0.01$) and less pleasant odours and fragrances ($r_2 = -0.26$, $p < 0.01$). In the blind closed conditions, similar relationships were present (humidity, $r_2 = -0.80$, $p < 0.01$, air freshness, $r_2 = -0.75$, $p < 0.01$ and air odours, $r_2 = -0.47$, $p < 0.01$). However, additionally the participants perceiving the air temperature as warmer was also found to be related to the participants reporting more unsatisfactory views ($r_2 = -0.33$, $p < 0.01$).

Air Quality Sensation

Relationships found between participants' perceptions of humidity, air freshness and air odours were the same in both blind open and closed conditions although there were slight differences in the strength of these relationships between conditions. A more humid perception of the air was related to the perceptions of less fresh air (Blind Open $r_2 = -0.82$, $p < 0.01$, Blind Closed $r_2 = -0.72$, $p < 0.01$) and more unpleasant air odours and fragrances (Blind Open $r_2 = -0.30$, $p < 0.01$, Blind Closed $r_2 = -0.46$, $p < 0.01$) in both the blind open and blind closed conditions. Additionally, a more pleasant sensation of air odours was found to be related to a fresher sensation of air quality (Blind Open $r_2 = -0.31$, $p < 0.01$, Blind Closed $r_2 = -0.44$, $p < 0.01$) in both blind open and blind closed conditions.

Noise Sensation

The perceptions of noise were unrelated to all other environmental sensations when the blinds were open. In the closed blind conditions, the perceptions of the louder conditions were found to be related to a brighter sensation of light ($r_2 = -0.22$, $p < 0.05$) and more unsatisfactory views ($r_2 = -0.21$, $p < 0.05$).

Lighting and View Sensation

When the participants reported brighter conditions in the open blind conditions, this was related to the perceptions of a more humid environment ($r_2 = 0.24$, $p < 0.01$) and less fresh air ($r_2 = -0.28$, $p < 0.05$). In the blind closed conditions, similar relationships were found to be present (humidity, $r_2 = -0.26$, $p < 0.05$ and air freshness, $r_2 = -0.28$, $p < 0.01$). However, when brighter conditions were perceived, this was also related to the participants perceiving more pleasant odours and fragrances ($r_2 = 0.32$, $p < 0.01$) and a louder sensation of noise ($r_2 = -0.22$, $p < 0.05$). Alternatively, darker perceptions of light brightness were found to be related to more unpleasant odours and fragrances and a quieter perception of noise.

The perceptions of the view were unrelated to all other environment sensations when the blinds were open. In closed blind conditions, the perception of unsatisfactory views was related to perception of warmer air temperatures ($r_2 = -0.33$, $p < 0.01$), a more humid environment ($r_2 = -0.33$, $p < 0.01$), less fresh air ($r_2 = 0.38$, $p < 0.01$), and a louder perception of noise ($r_2 = -0.21$, $p < 0.05$).

Summary

Several relationships may have resulted from the psychological effects due to the differing environmental perceptions. For example, in the closed blind conditions where the views outside were restricted for all participants, the participant perceptions of warmer air temperatures and louder noises were related to more unsatisfactory views. Experiences of both warmer air temperatures and louder noises are known to make the occupants feel more irritated and annoyed. This likely results in the more unsatisfactory response (Guan et al., 2020).

Additionally, it was interesting to find that even though the objective measures of light (lux) were not related to the objective noise levels (dBA), there was a perceived relationship between the perception of brighter conditions and louder noise perceptions. This suggests that there was either a psychological effect that altered the participants' perceptions of sound when the conditions were brighter, or the measures of average dBA and illuminance were not accurate enough to identify a relationship between the objective measures. Both hypotheses may be true as within the focus group, it was commented that when the blinds were closed (and it was subsequently darker), the participants perceived the conditions as being quieter and participants also seemed more focused.

Interestingly, the perceptions of air temperature and the level of brightness in either condition were unrelated. This is surprising as generally it is assumed that if there is an increase in the perception of brightness (provided by natural daylight), then people will also feel warmer as natural daylight is related to an increased exposure to solar radiation. The absence of a statistical relationship may be because when the blinds were closed and the participants perceived slightly darker conditions, the participants still perceived the environment as being warm. This created variance within the data analysed. This also suggests that the overly warm conditions were predominantly caused by internal thermal gains as opposed to solar gain. However, solar gains contributed to some extent as a relationship was found between the objective illuminance and the objective temperatures in Section 4.5.2 (p. 183). There was a statistical difference found in the operative temperatures between the conditions observed in Section 4.5.4.2 (p. 233).

4.5.5.2.5 Environmental Sensations and Health and Well-being

The sensation measures identified in the previous section were correlated with the health and well-being. Both of these were measured in the pre- and post-test to assess whether there were any significant relationships between the variables and whether the relationships differed between the blind open and closed conditions. In view of the large number of measures for health and well-being, this section only reported that the relationships that differed between the blind open and blind closed conditions were statistically significant ($p < 0.05$). A medium strength correlation ($R_2 < 0.30\pm$) was found. All significant results have been tabulated in Appendix H. The relationships for each sensation are reported below, followed by a discussion of the most interesting results found.

Air Temperature Sensation

In open blind conditions, the perceptions of warmer temperatures related to the participants described their level of fatigue as completely exhausted ($r_2 = -0.31$, $p < 0.01$), as their skin feeling moister ($r_2 = 0.30$, $p < 0.01$), and as the participants feeling dizzier ($r_2 = 0.42$, $p < 0.01$), and generally feeling bad ($r_2 = -0.32$, $p < 0.01$). The participants also suggested that they had to work harder to obtain the same level of performance ($r_2 = -0.30$, $p < 0.01$) in warmer temperatures when the blinds were open. In the blind closed conditions, only one differing relationship was identified. This suggested that when the air temperatures were perceived as warmer, they also perceived the office as less clean (r_2 = - 0.34, $p < 0.01$).

Air Quality Sensation

In open blind conditions, the perceptions of more humid conditions were found to be related to the participants perceiving that their skin was moister (r_2 = 0.35, $p < 0.01$). In closed blind conditions, a more humid sensation was related to the participants feeling that their eyes (r_2 = - 0.33, $p < 0.01$) and mouth felt drier (r_2 = - 0.30, $p < 0.01$), that they generally felt bad (r_2 = - 0.31, $p < 0.01$), and that the participants perceived that the office was less clean (r_2 = - 0.38, $p < 0.01$).

The participants' perceptions of air freshness were related to several health and well-being symptoms. However, all but one of the relationships were present in both blind open and blind closed conditions. In general, these relationships suggest that the perception of fresher air was related to more positive health and well-being responses in both the blind open and closed conditions[41]. The only differing relationship suggested that in the closed blind conditions, the participants perceiving fresher air was related to the participants reporting the office as being cleaner (r_2 = - 0.38, $p < 0.01$).

In open blind conditions, the participants identifying more pleasant air odours and fragrances was related to them perceiving that their lips were not dry (r_2 = - 0.37, $p < 0.01$). In closed blind conditions, this was related to the participants feeling confused (r_2 = - 0.31, $p < 0.01$) and the office being perceived as cleaner (r_2 = - 0.35, $p < 0.01$).

Noise Sensation

In open blind conditions, the perception of louder noise levels was related to the participants identifying that they felt that they needed to work harder to achieve their level of performance on the tasks set (r_2 = -0.32, $p < 0.01$). Two further results had an almost medium strength relationship. This suggests that the participants identified more headache symptoms (r_2 = 0.27, $p < 0.01$) and that their eyes were aching less (r_2 = 0.27, $p < 0.01$) when they perceived louder noises. No such relationships were found between the responses in the blind closed conditions. There were no other relationships present that had a strength > 0.30.

[41] Specifically, they identified that when the participants perceived fresher air, they reported their eyes aching less, less headache symptoms, better clarity in thinking, not feeling dizzy, generally feeling good, a better ability to concentrate, feeling more alert, and feeling less irritated with the tasks set. The correlation strengths and significance levels for these relationships can be found in Appendix H.

Lighting and View Sensation

In the open blind conditions, the perception of brighter lighting conditions was related to the participants reporting their eyes aching ($r_2 = -0.29$, $p < 0.01$). However, this result has an almost medium strength relationship. This was an unsurprising result as brighter lighting conditions are related to a greater experience of glare issues. However, in the closed blind conditions, this relationship was not present. In the closed blind conditions when the participants reported a brighter lighting sensation, this was related to the participants feeling less confused ($r_2 = -0.37$, $p < 0.01$). Therefore, when the conditions were darker, they also suggested that they felt more confused.

The participants' perception of the view was not significantly related to any of the health and well-being question responses in the open blind conditions. However, in the closed blind conditions, an unsatisfactory view was related to the participants finding it harder to think ($r_2 = -0.35$, $p < 0.01$).

Summary

The finding that the perceptions of warmer air temperatures and louder noise levels related to the participants feeling that they had to work harder on the tasks set in the open blind conditions suggests that the environment perceived in open blind conditions created an additional barrier to obtaining their optimum level of performance. Experiences of louder noise levels can be distracting to the occupants when they are asked to focus on a particular task. It is therefore logical that the participants felt they had to overcome this environmental factor. The perception of warmer temperatures affecting how hard the participants need to work on the tasks is potentially a by-product of the other health and well-being symptoms related to the perceptions of warmer temperatures. For example, this analysis found that in open blind conditions, the perceptions of warmer air temperature were also related to the participants feeling more exhausted, dizzier, and generally feeling bad.

Interestingly, the perception of louder noises resulted in the participants reporting their eyes aching less. This is an odd result as generally eye-related symptoms are associated with the perceptions of light as opposed to noise. However, we can speculate that perhaps the sensation of louder noise levels distracted the participants from noticing that their eyes were aching, thus a more favourable response was given. However, further evidence is needed to support this hypothesis. There were a few differing relationships identified when assessing the perception of the air quality measures. Considering that the air quality should have been similar in either office (as the windows were closed), this is an unsurprising finding. It is possible that the perceptions of fresher air had a psychological effect on the occupants. When the air was perceived to be fresher in the closed blind conditions, the office was perceived as being cleaner. Similarly, the perception of cooler temperatures and less humid air was also related to the offices being perceived as cleaner.

Lastly, it was interesting to find that in the closed blind conditions, when the light levels were perceived as darker and the views out were less satisfactory, the participants reported feeling more confused and finding it harder to think. Both of these features could have a negative impact on the occupant's ability to carry out their work. The relationship between the view out and finding it harder to think was also supported by the findings of the focus group. One participant identified this as a reason for preferring the blinds to be open.

4.5.5.2.6 Environment Sensation and Objective Productivity

The sensation measures identified in the previous section were correlated with the objective productivity measures used to assess whether there were any significant relationships between the variables and whether the relationships differed between the open and closed blind conditions. All significant relationships ($p < 0.05$) that differed between the blind open and blind closed conditions have been reported.

__Air Temperature Sensation__

In the open blind conditions, the participants perceiving a warmer environment was related to the participants typing faster on the text typing test ($r_2 = 0.23$, $p < 0.05$). However, their processing speed slowed ($r_2 = 0.26$, $p < 0.05$) when responding to the incongruent stimuli. In the closed blind conditions, the perceptions of warmer air temperature were related to a poorer performance in the long-term visual memory test ($r_2 = -0.21$, $p < 0.05$).

__Air Quality Sensation__

In the open blind conditions, the participants perceiving a more humid environment was related to the participants making more errors ($r_2 = 0.24$, $p < 0.05$) and poorer accuracy ($r_2 = -0.23$, $p < 0.05$) in the text typing test. In the closed blind conditions, the participants performed worse in the long-term visual memory test ($r_2 = 0.21$, $p < 0.05$) when they perceived a more humid environment.

In the open blind conditions, the participants perceiving a fresher air sensation was related to the participants typing slower ($r_2 = -0.43$, $p < 0.01$) but making less errors ($r_2 = -0.35$, $p < 0.01$) in the text typing test. This resulted in an improved accuracy score ($r_2 = 0.27$, $p < 0.02$) in the text typing test. The participants also had a slower processing speed when responding to the incongruent ($r_2 = 0.29$, $p < 0.01$) and control stimuli ($r_2 = -0.23$, $p < 0.05$)

when perceiving fresher air. In the closed blind conditions, these relationships not present and there were no other relationships found between the perceptions of air freshness and the performance in the tests set.

In the open blind conditions, the participants perceiving more pleasant odours and fragrances was related to the participants responding less accurately in the number search test (r_2 = -0.23, $p < 0.05$). However, they also achieved a better processing accuracy score when responding to the control stimuli (r_2 = -0.43, $p < 0.01$). In the closed blind conditions, when the participants perceived more pleasant odours and fragrances, they were quicker at responding to the data entry task (r_2 = -0.29, $p < 0.01$) but responded less accurately (r_2 = -0.32, $p < 0.01$). In the closed blind conditions when the participants perceived more pleasant odours and fragrances, their overall reaction speed (r_2 = 0.27, $p < 0.01$) slowed.

Noise Sensation

In the open blind conditions, the participant's perception of noise was unrelated to their performance on the tests. However, in closed blind conditions when louder noise levels were perceived, the participants overall reaction speed in the data checking test (r_2 = -0.21, $p < 0.05$) and their processing speed in relation to the congruent (r_2 = -0.25, $p < 0.01$) and incongruent (r_2 = -0.22, $p < 0.05$) stimuli were both slower. Similarly, the accuracy of their responses to the congruent (r_2 = 0.20, $p < 0.05$) and incongruent (r_2 = 0.23, $p < 0.05$) stimuli were worse. Louder perceptions of sound were also related to a poorer working memory score (r_2 = 0.30, $p < 0.01$) in the closed blind conditions.

Lighting and View Sensation

In the open blind conditions, brighter perceptions were related to fewer correct answers being entered for the data checking task (r_2 = -0.31, $p < 0.01$), a slower reaction time overall (r_2 = 0.25, $p < 0.05$), and a poorer processing accuracy score when the responses were provided to the control stimuli (r_2 = -0.31, $p < 0.01$). Short term (r_2 = -0.23, $p < 0.05$). Working memory (r_2 = -0.30, $p < 0.01$) was also negatively affected. In closed blind conditions, when the participants identified brighter conditions, the participants were quicker when conducting the number search task (r_2 = -0.24, $p < 0.05$), although the reaction times when the correct responses were provided (r_2 = 0.21, $p < 0.05$) slowed. In the open blind conditions when a more satisfying view was reported, text typing speed slowed (r_2 = 0.37, $p < 0.01$). The participants performed worse in the working memory task (r_2 = -0.23, $p < 0.05$). In closed blind conditions when a satisfactory view was perceived, more text typing errors were made (r_2 = 0.26, $p < 0.01$) and the participants had a poorer text typing accuracy performance (r_2 = -0.22, $p < 0.05$).

4.5.6 Methodology Review (Focus Group) (Objective E)

Braun and Clarke's (2006) six steps on how to conduct a qualitative thematic analysis were followed. These steps include:

- Familiarisation with the data
- Coding initial features and patterns within the text
- Searching for relevant themes
- Reviewing the themes
- Defining / reducing the themes into common themes
- Writing up an analytical report with integrated extracts of relevant data

A thematic analysis allowed for a more interpretive approach to be applied to the given answers as the meaning behind the use of certain words and phrases was able to be considered rather than just evaluating the frequency of when certain words or phrases were used. Two audio recording devices were used to record the focus group session which was transcribed verbatim by the researcher. Important inflexions, such as long pauses, laughter, unidentifiable passages etc. were noted within the transcription. The full transcript is presented in Appendix I. When coding the transcript, twenty-nine initial codes were generated and each code was split into either positive, negative, or neutral polarities, totalling to 87 sub-codes. The codes were applied to either the conversation between participants, phrases, sentences, and in some cases, words. For example, negative associated feelings with having the blinds down were given one code while positive feelings were given another. Responses that were neutral were given a third code. Each segment of text could be given more than one code if a participant expressed more than one view or conflicting views within the same sentence or phrase. The twenty-nine initial codes of the positive, negative, and neutral associations were then reduced to form fourteen sub-themes split into negative, positive, and neutral associations, grouped into three overarching main themes from the transcript. The three main themes and fourteen subthemes have been presented as an abbreviated thematic map in Figure 106. An extended thematic map is supplied in Appendix J which highlights the quotations that fit within each of the subthemes. In this section, each main theme is summarised and then disseminated into its subthemes. Example quotations made by participants are given to illustrate how they contribute to the subtheme and subsequent main theme. These examples are referenced in relation to the full focus group transcript by providing line numbers in superscript which relate to the line numbers in Appendix I.

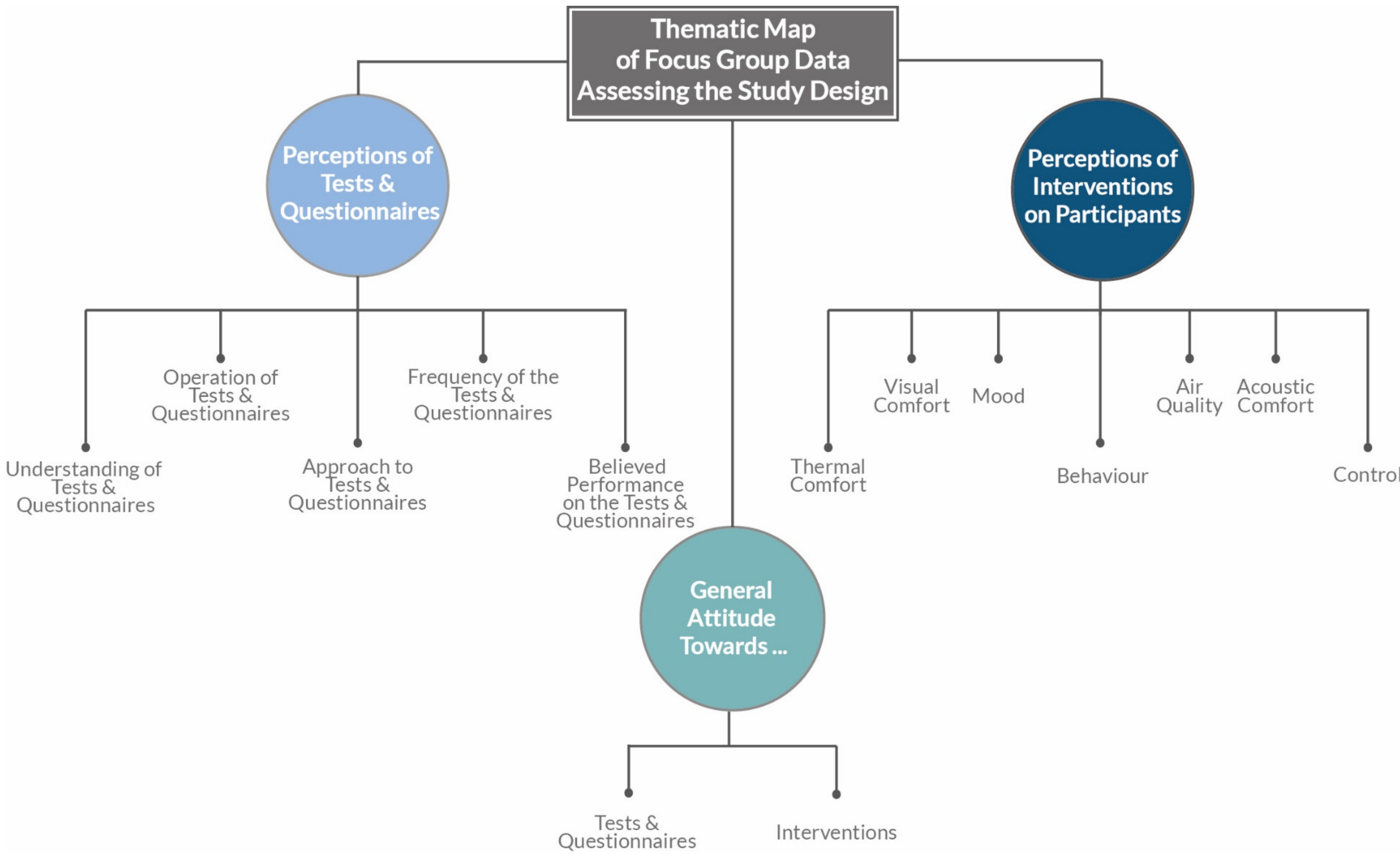

Figure 106. Main Themes and Subthemes generated from the Focus Group Data assessing the Study Design

4.5.6.1 Perception of the Tests and Questionnaires

This theme highlights the participants' perception of the test battery. The comments made by the participants related to the following subthemes:

- Understanding of the tests and questionnaires
- Operation of the tests and questionnaires
- Approach to the tests and questionnaires
- Frequency of the tests and questionnaires
- Believed performance of the tests and questionnaires.

<u>Understanding of the Tests and Questionnaires</u>

Most of the comments related to the participants' understanding of the tests and questionnaires were negative. Five of the tests were identified as being problematic:

- Grammar Test
- Data Entry Test
- Long-term Memory Test
- Short-term Memory Test
- Working Memory Test (Backward Digit)

The Grammar Test was described by one participant as they "…didn't have a clue what that was about…[119, P3]" Another participant questioned the intention of the tests and whether it was purposely designed "…to fluster you…[217, P4]".

In relation to the Data Checking Test, confusion was expressed about how the tests were being assessed: "I didn't know much about the specific reasons of the tests…[130-131, P9]" It was suggested that this may have influenced their approach to the task. They subsequently focused on improving their "…speed [131, P9]" when completing the task.

During the Long-Term Memory Test, some of the participants felt misinformed about the test. For example, "…I studied it as if it was gonna be long-term memory… but when it said long-term memory test next, I thought what do you mean?...[556-558,P5]" This was a shared opinion and other participants suggested that if they had known, they "…would have spent more time looking at them and remembering them if you knew… each week you had to do it…[409-410,P8]".

One negative and one neutral comment was made about the Short-Term Memory Test that criticised the transparency of the marking scheme as they were uncertain "…if it was a good thing to write something if you were not 100% sure or not…[233-234, P9]" This again implied that the absence of information about how the test was being marked may have influenced their approach to the task. The neutral comment relating to the test suggested that "…if they were told the task, I'll remember where, if I'm not told a task I won't…[180, P9]". The researcher infers this comment to mean that if they were told before the grammar test that they were going to be asked questions relating to the test, they would have taken more time to read the grammar test questions. However, this defeated the objective of the task which was to test short-term memory without prompting the participants regarding what they had to remember, although the participants were not aware of this intention.

Within the Working Memory Test, feedback was given on how they performed at the end of the task. This feedback was felt to be unclear and not fully understood by some of the participants, "I thought it lied. [476, P7]" It was described as "…confusing[502, P5]" "…demoralising…[486, P10]" and "…frustrated…[487, P10]" participants.

A general positive comment made by one participant about the Memory Tests suggested that some of the participants understood why there was a variety of differing memory tests: "I assume that's like part of the tests, different ways memory cognition work…[176-177, P9]".

1. Operation of the Tests and Questionnaires

Only negative comments were made regarding the operation of the tests and questionnaires. Five tests were referred to as problematic within the study design. These have been listed below along with a brief description of the operational issues:

Operations of Specific Tests:

- Data Checking Test
- Arithmetic (Plus and Minus) Test
- Text Typing Test
- Long-Term Memory Test
- Working Memory

General Operational Issues:

- Instruction pages
- Start time of the tests
- Pre-test behaviour
- Desk locations

The Data Checking Test was expressed to be "…a bit glitchy or I was not quite precise enough.[132-133, P9]" This was perceived to "…hinder your performance[135, P9]…". The Arithmetic (Plus and Minus) Test was described as temperamental as it was possible to mis-click. This would mean skipping a page when inputting the results on screen.

It was commented that one participant found the Text Typing Test problematic as the participant had been previously trained as a touch typist. In the first few sessions, they forgot to look at the screen when typing to know when the test had finished which caused the participant to continue typing when the test had finished. Even though this may have been "…frustrating[272, P5]" for the participant, it would not have negatively affected their performance in the Text Typing Test. It would have perhaps affected their performance of the preceding tests.

The duration of the Long-Term Memory Test was felt to be "… too long…[193, P10]" as a participant claimed that they would "type it up and then I'd go and do something.[193-194, P10]" Even though this would not have affected their performance of the test, their focus and the environmental conditions that they were in would have altered when moving away from the desk location being monitored, potentially affecting their responses to the post-test Health and well-being questionnaire .

When discussing one participants' approach to completing the Working Memory Test, the participant was met with joking shocked gasps from the rest of the group. The group viewed the participants' approach to the task as unfair. The participants admitted that they had written the answers down before entering them. This went against the instructions that were provided before the task was given. This identified a weakness in the operation of the test and the participants' approach would have affected the data collected as the task was aimed at testing memory recall.

It was commented that on one of the instructions pages, they were asked to "…hit enter but you didn't hit enter…[134, P9]" on the keyboard. They needed to use the mouse to click the enter button on the screen. It was also understood by the participant that this would not affect their performance on the actual test. However, the participant did find it "…slightly irritating[135, P9]".

The start time of the tests were approached in different ways by some of the participants within the offices. Within Office A, a non-specified group of participants planned that they would start the tests at roughly the same time, "…to start in our little pod… roughly… within 15 minutes of 12pm…[682-683, P10]" In Office B, it was explained that individuals starting the tests at different times disrupted those still completing the tests e.g., "…others who'd finished but come back… and they'd start talking and eating…[674, P1]".

Pre-test behaviours were acknowledged as potentially having an impact on their performance on the tests. One participant claimed to feel more "relaxed…[355, P10]" if they had been in the office a short time prior to the tests and questionnaires than if they had been in the office for a longer amount of time and it was a hotter day.

One participant raised the problem that the desk locations were an issue for them. The participant was required to work at a different desk location from their 'normal' desk location for the test. They expressed finding this "unsettling[697, P6]" as they were not used to hot desking within the office. Other participants who were used to hot desking did not consider this to be a problem.

Even though issues were raised by the participants during the focus group, it was not possible to ascertain whether all of the participants, a select few or just one participant experienced these operational problems. In summary, the operational issues were suggested to impact the participants in the following ways:

- Altered their belief that their performance in the test was affected.
- Affected their mood and/or attitude towards the test.
- Resulted in a behaviour change.
- A combination of the above occurred.

Where the operational issues resulted in participant error (e.g., Arithmetic (Plus and Minus) Test)) and/or the participants presented with the opportunity to cheat (e.g., Working Memory Test), a strong belief that their performance was affected was expressed. However, the occurrence of operational issues commonly created an associated feeling of frustration. This associated feeling stemmed from the participant's feeling as though the test was unfair or "…naughty[136, P9]". Where this occurred, the researcher hypothesised that subconsciously, the participant's mood and effort could have been negatively affected.

In some cases, the issues relating to the operational performance of the test resulted in a behaviour change. For example, when the Long-Term Memory Test was perceived as "…too long,[193, P10]" instead of waiting, the participant would "…go and do something[194, P10]". Similarly, the way that the Working Memory Test was delivered resulted in one participant cheating and using the differing strategies that were created by some of the participants in Office A to avoid noise disruption. The behaviour changes may have given an advantage to the same participants when carrying out the tests.

2. Approach of the tests and questionnaires

Negative and positive comments were made relating to the approach of the tests and questionnaires. Several participants discussed how they developed different strategies to complete the tests more successfully. This was specifically discussed in relation to the Working Memory Tests. One participant claimed to find a "…strategy that worked[154, P10]". During this discussion, it was disclosed that the strategy was perceived negatively by the rest of the participants and that it was deemed to be cheating as it defied the objective of the test. This was explained to the participants in the instruction sheet.

Approaches to the Long-Term Memory Test, Grammar Test, and the Health and Well-being Questionnaire were also discussed. Two participants claimed that they were "guessing[208, P5]" on both tests and one participant claimed that they "…stopped trying…[201, P5]" on the Long-Term Memory Test. One participant declared that they would always answer the same way "… I will always say 50%[239, P2]" on the Health and Well-being Questionnaire.

3. Frequency of the Tests and Questionnaires

All polarities of responses were made in relation to how often the tests and questionnaires were given to the participants to complete. Positive comments were made related to how they found them: "It did get easier… because you kind of knew what to expect[125-126, P10]." Further reasons were given for it feeling easier as they "…felt quicker…[407, P10]" The participants claimed that they "… got into the routine of it… [127, P10]". One participant suggested that there was more pressure in the first few sessions as "at the very beginning because you wanted to do so well…[555-556, P5]".

Specific tests such as the Data Checking and the Short-Term Memory Tests were commented on as being positively affected. They became easier as they "…could remember that that's what's gonna be asked[436, P8]" and they could concentrate more on what they were reading prior to the Short-Term Memory Test. A general comment made by one participant which stated that "two (tests per week) seemed, like manageable[577, P10]". However, other participants had conflicting opinions. It was mentioned that "The tests became quite routine…[186, P2]" and therefore "…too easy to keep on doing.[187, P2]" It was suggested that "You started becoming complacent…[452, P8]". Further to this, another participant stated that they "…found the two days were a bit much[589-590, P5]…" and it was suggested that "once a week would have been easier…[610, P5]". The frequency of the tests was also suggested to have a negative impact on the level of performance in the tests. The Long-Term Memory Test was thought to become boring because of how long they had to wait before the next task.

Differences of opinion were also expressed depending on how often the participants were completing the tests and questionnaire. Some of the participants were only able to complete one test per week and it was suggested that it would have been harder for some participants as they were not getting the same "…momentum. Or the repetition. [464-465, P10]" that the other participants experienced. Lastly, a neutral comment was made that suggested that how they felt about the frequency of the tests was related to how busy they were during the testing period as if they were "flat out[613, P10]" in their other work-related activities, they may have found it to be a "bit too stressful[614, P10]".

4. Believed Performance in the Tests and Questionnaires

Positive and negative comments were made about their believed performance in the tests. Negative general comments such as "I didn't do very well still [108, P3]" and "My performance was… poor.[280, P4]" were made. More specific negative comments were also made such as "I think the text typing I found most difficult[268, P5]" or the participants gave justification for their negative performance: "…for the first few tests I wasn't feeling well, I don't think so, I don't think I did so well on the tests[396-397, P6]". There was also suggested to be a sense of fear surrounding their performance in the tests with a joking comment made by one participant, "make sure this doesn't get back to my boss[181, P4]".

General positive comments were predominantly related to the frequency of the tests and the repetition in the presentation of the tests. Examples of comments made are "As it went on, you know, it felt that some of the things felt a bit easier [554, P5]" and "…you kind of knew what to expect, you knew what was coming[126, P10]" giving the sensation that if felt "less onerous[405, P10]".

4.5.6.2 Perception of the Interventions on the Participants

This theme highlights the participants' perception of the interventions on the participants. The interventions (open or closed blinds) were imposed on the participants to create variation within the thermal and visual comfort of the participants. Closing the windows and preventing the participants from using electric fans was required to reduce the variations in acoustic comfort, air quality and air velocity between the offices. Even though the interventions altered the environmental sensation, additional aspects such as changes in mood, behaviour, and the perception of control in the offices were subsequently felt by the participants because of the interventions.

The comments made by the participants were related to the following subthemes:

1. Thermal Comfort
2. Visual Comfort
3. Air Quality and Acoustic Comfort
4. Mood
5. Behaviour
6. Control

These aspects have been described below.

1. Thermal Comfort

Negative comments made regarding thermal comfort suggested that the participants perceived that "…having the windows down" … was the cause for the office feeling "…far too hot on some sessions…[663, P10]". This was described as "…pretty grim…[80, P3]" when they experienced "…some pretty high temperatures[80, P3]". It was also believed that having the blinds closed made "The offices (are) warmer.[49, P8]" which was initially questioned by another participant, "Do you think?[50, P10]" This was then reasoned that the environment "…felt enclosed. So, the inside felt a lot warmer…[52, P8]" indicating that having the blinds closed influenced their perception of the conditions rather than the actual temperature.

When the "horrendous heat" was combined with having a "lack of sleep" the night prior then "… it really did, I felt, degrade your ability.[368]" Another mentioned that if they "had a lot going on in the office and it was really hot and sticky and really headachy… by the time they got to the test they were really, really angry.[378 - 380]".

2. Visual Comfort

Positive, neutral, and negative comments were made in relation to the perception of Visual Comfort. The neutral comment made stated that "…they (the blinds) altered the light…[41, P9]". When the new blinds were compared with the previous shading system, positive comments were made about the new shading system. The new shading system was perceived to improve the view outside of the offices. For example, "I liked the fact … when they were down I could still see out.[34,P5]" and associations were made with being "…connected to the outside world. [38-39,P4]" This was found to be subsequently related to improved productivity as one participant said "… when I think or I try to settle information in my brain I like to look out of the (short laugh) window at the tree or something…. So, I actually like the fact I can still see outside.[35-37, P5]".

Further positive comments were made that suggested that the blinds "…are better for the purpose of it's too sunny I need to pull the blinds down.[46-47, P10]" and that they "…were of value when it was really sunny as you have no other choice but to have the blind down.[41-43, P9]". Whilst it was not stated within the focus group, the researcher believes that this was due to the roller blind fabric allowing more natural daylight into the offices (when closed), providing more of a view because of the darker fabric colour selected.

There were some negative comments made related to the office being "…dark…[48, P10]" and "…dingy.[48, P10]" when the blinds were closed. Similarly, it was mentioned that when the blinds were closed, the electric lights "were a lot stronger[45, P9]" and one participant claimed that they "don't (didn't) like artificial light[45, P9]". When the blinds were open, the daylight was described as "…harsh.[95, P4]" on occasion.

3. Air Quality and Acoustic Comfort

Only negative comments were made regarding Air Quality in the offices. For example, "not having any air in, made it… slight smell, and you come in and it's like you'd notice immediately…[89, P9]". This was linked to having the windows closed which also impacted the participants positively in terms of their acoustic comfort. It was described that "… the quietness in our space, was just like a relief.[664, P10]" by one participant. The constraint of having the windows closed during the test sessions led another participant to comment that they were "more aware of noise and the traffic going past…[713-714, P3]".

Further neutral comments were made relating to the level of acoustic comfort in the office. The participants observed that the interventions "…affected the atmosphere as well… It felt very quiet. [54, P1]" This was perceived by the colleagues as helping them to seem "more focussed and quieter[63, P9]" which can also be categorised as a behaviour change.

4. Mood

Only negative comments were made regarding the interventions placed in the offices and the effect that they had on the participants' mood. When the blinds were closed, the environment was described as "…a little bit depressing. [38, P4]" Similarities were drawn to being in "…a sad National Trust Place where the fabrics fade...[44, P9]". The conditions were perceived to make "the office look more clinical…[69, P7]". The impact of open blind conditions were not discussed in relation to mood.

One of the offices required partitions to be installed and this was claimed to impact the mood of one participant as they felt less like "part of a team[26, P4]". As there were no team tasks, this was unlikely to have affected the participants' performance in the tests but it perhaps affected the mood within the office and their day-to-day work duties. Others preferred having the partitions in place, but no reason was given for this.

Changes in the thermal comfort conditions altered the participants' moods negatively as previously described. This feeling was exacerbated when the other factors were also reported as negatively affecting them. One participant described feeling "really, really angry… [380, P80]" which was perceived as out of character. This was caused by the combination of warmer temperatures and a busy workload which they felt inflicted headachy symptoms.

5. Behaviour

The participants' behaviours were affected when the blinds changed position. When closed "…they (the blinds) affected the atmosphere as well… it felt very quiet[54, P1]" which made the participants perceive the office atmosphere to be "…more focused and quieter…[63, P9]" during the test sessions. Additionally, because the participants had to complete particular tests and questions under the specific interventions that differed from their normal working conditions, they were aware that they were being tested. One participant claimed that you realised you "were in a test environment, (so) you might not have said things that you would have done so openly as you perhaps did in the afternoon[66-68, P5]". This suggests that the Hawthorne Effect could have been present. This is where the participants' performance improved in a set of tests because of their awareness of being tested and observed (Schwartz et al., 2013).

The observations from the participants above reveal that both the blinds being closed and the awareness of being tested likely affected the participants' performance in the productivity tests. The former in a positive way and for the latter, there is no polarity associated with the change in behaviour caused by their awareness of being in test conditions. The previous research suggests that a positive effect may have occurred.

6. Control

Only negative comments were made in relation to "Not being able to open and close the windows or turn on the fan.[78, P7]" and adjusting the lighting. The interventions were suggested to alter the participants' mood as they were described as finding it "a bit frustrating [83-84, P3]" and "very difficult" for them. This negative association was directed to the limited control given to the participants caused by the aspiration to control the office environment more freely. One participant claimed that they "…wish(ed) I could have opened the window a bit more often at times.[327-328, P3]" Further comments suggested that it was perceived to be "better to have the windows, blinds up…[59, P4]". It was proposed by one participant that if they were in a "…normal environment I would be opening and shutting the windows[99, P5]" and "normally my blinds…. Would be halfway down just so it stopped people getting sunlight in their eyes[101-102, P5]" although they would not necessarily use the fans as they disliked the "feeling of the fan on me [them][101, P5]."

4.5.6.3 General Attitude towards the Interventions and the Tests and Questionnaires

The remaining comments made by the participants were either general or abstract comments relating to the interventions or tests and questionnaires. The comments were split into the following two groups.

1. Interventions

Positive, negative, and neutral general comments were made about the interventions. The participants suggested that the trunking on the floor that was used to protect the participants from tripping over the cabling and the installation of the partitions in one of the offices was problematic. The reasons given suggested that they were "…too long…[193, P10]" for the desks and this affected the participants' perception of safety within the office. However, some of the participants were noted to prefer having partitions in their office and they stated that they "…were going to keep them up (partitions) going forward[16-17, P2]".

Concerns were also raised about how the interventions (windows closed and blinds either open or closed) may have subsequently affected their 'normal job' duties outside of the test conditions. One participant suggested that they felt "… on some days I thought that (it) was alright and other days it was (like that was) terrible[359-360, P10]" Another stated that if the "… windows (were) open (it) would affect me more...[394-395, P6]". Positive comments were also found related to the participants preferring the newly installed blind system, "the new ones are better…[62, P4]".

2. Tests

Both positive and negative comments were made in relation to the tests and questionnaires. The participants suggested that they "…enjoyed doing it…[119, P3]" as some tasks were seen as "…good fun (referring to the Processing Speed and Accuracy (Stroop) Test)…[P323, P3]" Others said that the "first few sessions you were kind of, I was kind of excited about it…[544, P5]" which was related to being excited as "…it was for your research…[550, P5]". Positive comments were also made which identified the participants' understanding of the study design and how the tasks were related to their day-to-day job duties. The tests given were felt to have "…covered different components…[331, P5]" and they were described as covering "... a range of different skills and attributes that we possibly might be using on a particular day…[333-334, P4]."

The Arithmetic, Reaction Time, Processing Speed and Accuracy (Stroop), Text Typing and Grammar Tests were specifically mentioned as being related to their job activities as they require similar skills to those used when writing emails and making work decisions. One participant also commented that they were aware they were given tests related to the skills that they use: "…subconsciously (anyway) in a day… in our daily activities…[336, P8]" and they may not have "…realise(d they) were doing it…[337, P8]". Negative comments were also made by some of the participants who did not understand how the tests (apart from the Text Typing test) "…really, really helped to be honest[219, P2]". This was further commented on by another participant later on in the transcript who spoke on behalf of a group of participants who suggested that it was "…harder for us to understand the relationship between the performance of the tests and our actual roles not because there isn't one, it's just not directly related unlike others in different roles. Like someone with more of an admin job. [340-343, P9]." Some of the participants suggested that the process made them feel "thick…[110, P4]" and they feared the results getting back to their superiors as the researcher was asked to "make sure this doesn't get to my boss, ok. [181, P4]". Others expressed feelings of sadness and questioned the relevance of the questions posed in the Health and Well-being questionnaire. For example, one participant was saddened by reflecting on the condition of their hair because they had no hair to reflect on. Additionally, the condition of one participant's nails was felt to have nothing to do with their work environment and related more to the DIY that they were doing at home.

Another participant stated that the tests seemed to identify "…what you felt about the environment and everything but if you were feeling like really crappy in the morning and you were affected by different factors…[369-371, P3]" where there "was one little question saying yes, no, maybe (external) factors and I thought that was one of the things that sort of worried me…[372, P3]". This comment implies that the questionnaires did not seem to fully assess the external factors that could be affecting the occupant's productivity.

4.5.6.4 Summary

The following section summarises the possible improvements that could be made in future studies to reduce the unintentional variations in the data collected.

Improvements to the Tests and Questionnaires

The participants' perception of the tests was influenced by their understanding, the operation and the frequency of the tests which subsequently affected their approach, and their believed performance in the tests and questionnaires. Practice effects and questionnaire fatigue were symptomatic of the frequency and length of time of the tests, as well as their understanding and operation of the tasks. Even though these issues may not be able to be fully eliminated, it is likely that the impact that they had on the data collected can be reduced. This could be done by:

- Reducing the number of questions and tests to shorten the length of time that it takes to complete the tests e.g., from 30 - 45 minutes to a more reasonable 10 - 15 minutes.
- Improving the quality and relevance of the tests and questions e.g., preventing the participants from cheating and altering the scale and presentation of the health and well-being conditions.
- Increasing the number of variations in the test or having a larger participant population to allow for a reduced frequency of testing e.g., one test per week.
- Providing rewards and non-specific feedback upon the completion of the tests to encourage their completion.
- Engaging the line-managers of the participants so then the participants are encouraged to participate.
- Communicating to the participants that the purpose of the study is to identify how their surroundings are affecting them as opposed to identifying how well they as individuals are performing.

Even though the alterations may still result in different approaches being taken by the participants, the improvements made will reduce the variation in the approaches to the tasks and make it a fairer test between the participants e.g., the participants would be unable to cheat.

<u>Improvements to the Interventions</u>

The participants suggested that the interventions imposed (i.e., fixed shading and window position) influenced their feelings towards the internal environmental conditions which subsequently affected their mood, behaviour, and attitude because of the restricted control that they had within the internal environment. This suggests that a 'control' factor also influenced the participants' responses and that this may have led to an additional variation in the responses reported. However, as the purpose of the study was to identify the impact of shading position (closed or open) on the internal environment conditions and the occupant's perceptions, the study design needed to control the position of the blinds and the window position to control and reduce the variability in the other factors (e.g., air velocities, internal temperatures, air quality, and acoustic conditions) that would have also subsequently affected the participant's responses.

It is unlikely that any changes in the design of the study could eliminate this 'control' factor. Evaluating an uncontrolled environment would only help to identify how the blinds are used to maintain a comfortable environment, although it is likely that not all of the occupants would report comfortable conditions under the same environmental conditions. A more longitudinal dataset could be collected in an uncontrolled environment but similarly it is unlikely that enough comparative data (e.g., blinds open and closed data collected under the same external environment conditions and similar internal environment constraints) would be collected.

It was also highlighted that the installation of equipment in the office spaces meant running wired cables with electric cable trunking covering the cables to prevent the occupants from tripping. However, in some areas of the offices, this was problematic for the participants even though the appropriate precautions were taken to ensure the participants' safety. Interestingly, it was also acknowledged that the participants observed differences in their acoustic and air quality comfort between the testing and non-testing days. This was not the intention of the study but a subsequent effect of controlling the window position within the study design. Lastly, one participant suggested that on some days, there were longer lasting negative effects on the occupants' mood caused by the test conditions. This was suggested to have a detrimental impact on their work productivity during the normal working day preceding the test session.

The researcher believes that the following measures could be taken to improve the study design:

- Using wireless sensors and logging equipment or collecting the data via an integrated BMS (Building Management System) could be used to:
    - Reduce the interference of the monitoring equipment on the participants.
    - Allow for the monitoring of both pre- and post-test sessions.
    - Monitor the internal conditions more closely to avoid extremes in condition over a prolonged period.
- The incorporation of 'real-world' productivity metrics where the participants carry out similar tasks e.g., the volume of call rate, where possible.

- The incorporation of wearable technologies that monitor the objective health metrics to evaluate the longer lasting symptoms of the indoor environmental conditions.
- The monitoring of occupancy and other air quality metrics (VOCs) to reduce the ambiguity in the interpretation of the results.

4.6 Summary

This study set out to identify whether there was a relationship between the internal environment conditions and the movements in blind position. Within the study, the 19 participants were spread across two normally naturally ventilated offices. In both offices, the windows remained closed and the internal roller blinds were alternated between being either fully closed or fully open during a warmer weather period. Between 12 noon and 2 pm[42] on two days of the week over 15 weeks, the participants were asked to answer a set of questions and tests while the internal and external environment conditions were monitored. The questions and tests assessed how they perceived the internal environment conditions, their overall comfort level, their health and well-being, their productivity level, and their performance in various cognitive and work-based tasks. Lux sensors and operative temperature sensors collected the environmental data locally of each participant, as well as the air temperature, relative humidity, CO_2 levels, and noise levels (dBA) taken centrally within the two offices.

__Relationship between blind position and the internal objective environment conditions__

The first objectives were to evaluate how the position of blinds altered the objective internal environment conditions and how this in turn varied and predicted the participants' responses to and performance in the questions and tests. To establish if there was a statistically significant relationship between blind position and the internal environment variables (Objective A), a Spearman Rho rank correlation was carried out on the data collected. The analysis found that relative humidity ($r_s = 0.23$, $p < 0.01$), operative temperature ($r_s = 0.16$, $p < 0.05$), and internal illuminance all increased ($r_s = 0.89$, $p < 0.01$) when the blinds were opened. All other environmental measures were not directly related to blind position. The literature supports the finding that operative temperature and internal illuminance are affected by blind position because of the variations in the amount of solar radiation entering a space (Littlefair, 2017; Seguro and Palmer, 2016; Wouter et al., 2010). However, the positive relationship that relative humidity had with blind position is

[42] This time range differed depending on when the participants started and how long the participants took to complete the test battery.

unsupported. Potentially unmonitored rainfall, the narrow range of internal environment conditions monitored, and other unmonitored factors (i.e., occupancy and respiration rates affected by changes in temperature) contributed to this finding. Collecting the data over a broader range of environmental conditions (specifically humidity) with the addition of monitoring rainfall and occupancy would help to prove or disprove this relationship.

Subsequent Effect of the Variations in the Internal Environment on the Subjective Perceptions and Objective Productivity

The further objective of identifying whether the variations in the internal environment altered the participants' subjective perceptions and objective productivity were evaluated by entering the responses of the test battery as a dependent variable and entering the internal environment measures as an independent variable into a hierarchical regression. Through regression analysis, the amount of variance created within the test battery responses contributed by the environmental variables were identified.

The results of the internal environment questionnaires identified that the variations in:

- Operative temperature altered the participants' responses to the thermal comfort and air quality questions by 1 - 2 % and the visual comfort questions by 1%.
- Air temperature altered the participants' responses to the thermal comfort questions by 3 - 17%, the visual comfort questions by 9 -17%, the air quality questions by 5 - 11%, and the noise sensation question by 3%.
- Lux levels altered the participants' responses to the thermal comfort questions by 1% and the visual comfort questions by 11 - 32%.
- Relative humidity altered the participants' responses to the air quality questions by 6%.

The responses to the overall comfort and subjective productivity questionnaires identified that variations in:

- Operative temperature and air temperature altered the participants' responses to the overall comfort question by 1 - 6%.
- Lux levels, operative temperature and air temperature altered the participants' responses to the subjective productivity questions by 1%, 1 - 6% and 15% respectively.

The results of the health and well-being questionnaires identified that the variations in:

- Operative temperature and air temperature altered the participants' responses to the pre-test questions by 3 - 6% and 1%, respectively
- Operative temperature and air temperature altered the participants' responses to the post-test question by 5 - 12% and 1 - 6 %, respectively.

Lastly, the performance of the objective productivity and cognitive function tests identified that the variation in:

- Operative temperature and air temperature altered the participants' text typing speed by 7% and 1% respectively.
- Operative temperature and air temperature altered the participants' performance in the cognitive function tests by 1 - 6% and 1 - 7% respectively.

Approximately two thirds of the tests and questions assessed produced significant regression results. Operative temperature was found to contribute variance most frequently to the measures that met the significance level. Overall operative temperature provided a variation of 70% of the significant results/responses considered within this study. The health and well-being and thermal comfort questions were the most consistently affected by operative temperature, suggesting that the variation in exposure to the mean radiant temperatures affected the way that the participants perceived their health and well-being.

Over the duration of time, the participants responded to the health and well-being questionnaire the operative temperatures differed by 14°C (between 25.6°C - 39.1°C). The large number of significant results found suggests that the variations in operative temperature affected the occupants' perceptions of their health and well-being. This is an interesting finding particularly when operative temperature is not often measured in buildings. This is because typically, air temperature is favoured. Even though air temperature was also found to predict and vary across the health and well-being responses, air temperature contributed less variation and was a weaker predictor of the participant's responses. Operative temperature includes the consideration of both air velocity and mean radiant temperature. As the air velocity did not vary, this suggests that the inclusion of mean radiant temperature both varied and better predicted the participants' responses to the questions.

The variation in responses attributed to the internal environment conditions in the tests and questionnaires ranged widely between 3 and 40% depending on the test or question evaluated. The internal environmental conditions explained more of the variance when there was a broader range of internal environment data collected. For example, 40% of the variance in responses could be explained in the visual sensation question and only 3% of the variance in responses could be explained in the noise sensation question. In this study, internal illuminance conditions varied widely between approximately 100 and 1,000 lux. However, there was only a small range in noise levels of 15 dBA. The lack of variance explained by the internal environment conditions may also suggest that either the tests and questions used were not robust or that they were not understood by the participants. Alternatively, overriding factors outside of what was measured and included in the regressions may have altered the participants' responses to the tests and questionnaires (e.g., differences in clothing level and occupancy levels). Nevertheless, the results are representative of the conditions that the data was collected within.

Furthermore, from the results of the regressions we can ascertain whether an increase in an internal environmental variable predicted a better or worse score/response to the tests and questionnaires. The internal environmental measures that were found to differ due to blind movement (i.e., air temperature, operative temperature, and internal illuminance) were also the best predictors of change in participant responses and test performance.

A 3°C increase in *operative temperature* predicted:

- The occupants perceiving less glare issues and more unsatisfactory views.
- The occupants being less willing to exert effort on the tasks set (i.e., they were less motivated).
- More negative symptoms associated with nineteen out of the twenty-three health and well-being questions.
- A slower text typing speed by 3 WPM and a 0.5 better working memory score.

A 1.6°C increase in *air temperature* predicted:

- A warmer thermal sensation response and 'less acceptable' thermal conditions.
- A 'more humid' and 'stuffier' air quality perception and a preference for more pleasant odours and fragrances.
- A noisier acoustic environment.
- A preference for brighter lighting conditions.
- The occupants feeling more uncomfortable.

- The occupants believing that their productivity was affected (the question used could not determine whether it was being affected positively or negatively).
- More negative symptoms associated with four of the twenty-three health and well-being questions.
- A 1 second slower response time on the number search task.

A 259 lux increase in *illuminance* predicted:

- The occupants perceiving 'brighter' and more acceptable lighting conditions, perceiving the questionnaire as easier to read. They reported that the external view was more satisfactory.
- A 4.2% better processing accuracy score regarding the incongruent stimuli on the cognitive function tests.

While the relationships were supported by the previous research literature, several other significant predictors identified relationships that were unable to be corroborated. Very few studies that have tried to identify the impact of changes in the internal environment have been carried out where multiple environmental measures were evaluated. Frequently, one or two measures are altered whilst the others are held constant, therefore further research is needed to identify how the internal environmental variables interact with each other and subsequently affect occupants to support the findings found in this study. However, being able to reproduce the exact environment conditions is problematic in real-world offices that are reliant on natural ventilation as the internal conditions are affected by the varying external conditions.

Considering how many of the health and well-being measures (which are associated with Sick Building Syndrome) were negatively affected by an increase in operative temperature and were not affected by daylight exposure, it is likely that the operative temperature outweighs the benefit of internal illuminance. In some of the results of the regressions, this conflict can be observed within the significant predictors of the variables. However, it is likely that if the thermal conditions were perceived as thermally neutral by the participants, then the operative temperature would have varied and predicted fewer responses.

Operative temperature was also found to negatively affect the participants' willingness to exert effort on the tasks (a measure of subjective productivity). However, when assessing the objective measures of productivity, all environmental variables were found to influence their performance in the tasks set. Depending on the cognitive ability required e.g., working memory, processing speed, text typing etc, the environmental variables influenced the tasks differently, many of which are unsupported in the research literature. This is likely due to the incorporation of multiple environmental variables. The findings that were corroborated by the research literature were significantly related or differed due to the blind movement (i.e., operative and air temperature and illuminance). This suggests that closed blind conditions improved the text typing speed and response time in connection to the number search task due to the decrease in temperature. However, the closed blind conditions negatively affected working memory due to the decrease in temperature and the performance of the processing accuracy test due to the decrease in internal illuminance experienced.

Comparing the open and closed blinds conditions

The data set was also split by the interventions (open and closed blind conditions). Comparisons were made between the internal environmental conditions that each participant experienced over the duration of the tests and questionnaires. An average measure was calculated for each participant when they were in the open and closed blind conditions. This suggests that the air temperature (Mean Difference (MΔ) = 0.46°C), relative humidity (MΔ = 3%), CO_2 (MΔ = 26 PPM), and dBA levels (MΔ = 0 dBA) did not differ when the mean measures were compared between the groups who could be located in either of the two offices. However, and somewhat expectedly, internal illuminance (MΔ = 466 lux) and operative temperature (MΔ = 1.27°C) did. The differing position of the blinds affected the amount of solar radiation entering the offices, resulting in the observed differences. The internal illuminance levels were greatly affected where there was only a small difference in the internal operative temperatures. The small difference suggests that the solar gain in this building was not the only contributing factor to the overly warm internal conditions experienced by the participants.

A means paired t-Test was then carried out between the mean environmental conditions that each participant was exposed to between the two interventions. This in effect would rule out the variations created by differences in the participants' desk locations as all of the participants carried out the test at the same desk location in each test session. This analysis found that operative temperatures ($p < 0.001$) and internal illuminance ($p < 0.001$) significantly differed to an extent that would likely be noticeable by the occupant between the open and closed blind conditions. The upper and lower 95% confidence intervals identified that those in the open blind conditions experienced:

- Operative temperatures that were between 2.2°C and 0.8°C warmer.
- Illuminance levels that were between 510 lux and 410 lux brighter.

The analysis also found that the air temperatures significantly differed ($p < 0.05$). However, the amount by which they differed was negligible when taking into consideration the sensitivity of the sensors. The differences in operative temperature were also relatively small between the conditions. Additionally, in this analysis, no statistical difference was found between the relative humidities ($p = 0.09$). These results suggest that the main internal environmental variables that were affected by the opening and closing of blinds whilst the tests were carried out were in illuminance and operative temperature. The increase in internal illuminance made a noticeable difference where potentially small increases in operative temperature may not have been noticed if the participants took other actions to make them feel cooler (e.g., if they had a drink of water or adjusted their clothing level).

To identify the impact of open and closed blind conditions on the occupants, a between 'groups' analysis and a between 'individuals' analysis was conducted. The individual analysis assessed each of the individual participant's mean response to the questions in the blinds closed and blinds open conditions (i.e., it compared their own personal responses) using a means paired t-Test. The group analysis used the Chi-square method to compare the distribution of the responses reported by the two groups of participants (i.e., those in open and closed blinds).

Significant differences were identified between the groups of participants in the open and closed blind conditions. These differences were found to be related to the perceptions of visual comfort, air quality, and subjective productivity. The results identified that the participants in open blind rooms felt the following:

- That their productivity was being affected by the internal environmental conditions experienced[43].
- That the conditions were less humid.
- That the conditions were brighter and more visually acceptable.
- That there was less glare, and the visual task was easier to read.
- That they were more satisfied with the view.

Within the individual analysis, additional measures were identified that significantly differed between the two conditions. They were related to the same aspects (visual comfort, air quality, and subjective productivity) but they also identified differences in the

[43] No positive or negative association could be assigned to the question due to the question posed.

perception of thermal comfort. The results additionally identified that the participants in open blind rooms felt the following:

- More willing to exert an effort in the tasks set.
- That the conditions were warmer, and that they would prefer cooler conditions.
- That the air was fresher.
- That they preferred brighter conditions and experienced less visual strain.

However, not all measures were significant in both the group and individual analysis. Those that differed were related to the belief that the indoor environment was affecting their productivity, as well as the sensation of humidity and their experiences of glare.

In both methods of analysis, the blind position did not significantly differ participants' responses to the subjective comfort question and the health and well-being questions, even though illuminance and operative temperatures significantly differed between the two environments. However, the difference in temperature was relatively small (between 2.2°C and 0.8°C). Even though the differences in internal illuminance were larger (between 510 lux and 410 lux), illuminance only predicted a small number of health and well-being responses when the entire dataset (i.e., participants in both open and closed blind conditions) and the range in illuminance experienced by the participants was much larger (900 lux between the min and maximum illuminance level experienced). Additionally, even when the illuminance levels predicted the participant's responses, they were not the strongest predictor.

The individual analysis was felt to have found there to be more significant results between the conditions because there was less variability in the data. Variability caused by the occupant's individual physiology (e.g., caused by differences in gender, age, thermoregulatory, visual, olfactory, and auditory systems, and personal preferences and expectations), psychological behaviours (e.g., clothing level, behavioural responses to the environmental conditions, and the method of answering questionnaires), and the desk locations within the office made the comparison fairer and the results more robust. However, the group analysis helped to identify the general perceptions of the conditions despite the individual differences between people's perceptions.

The individual analysis method (means paired t-Test) was also used to analyse the objective productivity scores. This found that the participants in the open blind conditions:

- Typed 3% more words per minute. However, the processing accuracy of the control stimuli decreased by a mean of 1% compared to the participants in closed blind conditions.

Both findings disagree with the results of the regression analysis which show that an increase in temperature predicts a slower text typing speed and an increase in illuminance improved processing accuracy. This results in uncertainty in relation to the impact of a blind position to objective productivity.

Methodology Review

The focus group provided a platform for the participants to voice their views on the testing methodology. The focus group proved beneficial insights regarding the data collected, which was used to refine the data set to improve the robustness of the dataset (e.g., excluding the participants that cheated on the tests). However, several factors were highlighted that could have created further variance within the dataset, therefore allowing for the collection of data that was not evident in the structured questions in the test battery.

The discussion has identified that five of the productivity tests and some of the questions were misinterpreted or simply did not perform as intended. In some cases, it was identified that defects in the operation of the tests resulted in a change of participant behaviour. Their mood, attitude, and belief in their performance became altered, and consequently this created additional variances in the test data. This helps to explain why inconsistent results were found between the statistical analysis techniques used to analyse the objective productivity measures and it may also have contributed to why very few significant results were found. The participants also identified the symptoms of questionnaire fatigue and a lack of understanding in relation to the health and well-being questionnaire. This may have also contributed to why no significant results were found when assessing how the position of the blinds affected their responses to the health and well-being questions.

In relation to the impacts of the interventions, only negative comments relating to the warm conditions and poor air quality were experienced. Some neutral and positive comments were made regarding the acoustic conditions. It was noted that when the blinds were closed, the occupants seemed quieter than normal, and it was suggested that the participants behaved differently. This demonstrates that the participants were aware of the impact that the interventions were having on their perceptions of environment, comfort, health, and well-being. A mix of positive, negative, and neutral comments were made relating to the visual comfort conditions within the office. For example, having the blinds closed was identified to be problematic due to the darker conditions and diminished view. However, the participants commented that the newly installed shading devices were better than the previously installed shading devices as they provided a better connection to the outside and more daylight in the office space when they had to be down. The participants also expressed a great amount of frustration with their lack of ability to access fresh and cooler air. Even though it was acknowledged that the acoustic conditions improved when the windows were closed, within the discussion it seemed as though the participants' preference for better air quality and cooler conditions outweighed the acoustic benefit of having the windows closed. Lastly, and perhaps most interestingly, there was conflict between the participants' perception on whether the position of the blinds provided cooler internal conditions. When answering the thermal comfort questions participants suggested that in closed blind conditions, they felt cooler, however within the focus group not all participants were certain whether the position of the blinds made any difference to the internal temperature conditions.

Other more general comments were also made regarding the overall testing methodology. The participants seemed to grasp an understanding of the importance of the research. They commented that the tests did not relate to their job duties although they acknowledged that they use several of the skills without thinking.

Overall, the participants within the focus group identified several issues with the test battery and test design that could have caused a wider variance in the dataset. The focus group analysis allowed the researcher to reflect on the study design to identify how improvements could be made (see Section 4.5.6.4, p. 289). This should be taken into consideration when conducting further real-world stud

CHAPTER 5. ACOUSTIC PERFORMANCE OF SHADING FABRICS

5.1 Overview

The 'curtain' of a shading product is the main part of the product that covers the glazed area of a window. The curtain is typically made from fabric, wood, or metal. This is the main part of a shading product that prevents sound from entering a building or reflecting off hard glazed areas when extended (closed). Previous literature suggests that the acoustic impact of internal shading products on the internal acoustic environment is limited but nevertheless they do alter both the sound transmission and the sound absorption of a room (Matos and Carvalho, 2010, Catalina et al., 2019). Within this literature very few shading fabrics have been assessed for their acoustic properties and where the acoustic performance of shading products has been determined the results did not conclusively identify the impact these products can have on an occupants' perception of sound, or conclusively identify the acoustic absorption a shading product could provide to a typical room when installed. This lack of research may contribute to why shading products and fabrics are not considered in acoustic evaluations of buildings even though shading products are sometimes used within building design to improve the acoustic conditions. Shading products and fabrics that are chosen for their acoustic properties are typically installed to help reduce reverberant sound in heavily glazed buildings (e.g., atriums, conservatories) or to improve the sound insulation in buildings that cannot upgrade their windows (e.g., heritage buildings) (Historic England, 2016).

This research focuses on identifying the acoustic properties of eight shading fabrics used in internal shading products and conventionally installed in domestic and non-domestic buildings in the UK. When assessing the acoustic absorption properties some consideration was also given to the mounting distance that the shading products were installed at. Existing test methods were explored and evaluated, and where possible relied on to evaluate the sound insulation and the sound absorption performance of the shading fabrics. The acoustic performance of these fabrics were compared and where possible the results of these tests were included in early-design acoustic calculations to identify the extent that the shading products could theoretically affect the internal acoustic conditions. From the testing of the fabrics, conclusions are drawn that could help manufacturers of shading fabrics identify and produce new fabrics that reduce the transmission of external noise or amount of reverberant sound within a room. The limitations of this work are that the method of installation (i.e., the way the fabrics are installed to the window area) was not fully considered in the testing as only a limited number of mounting distances were assessed. Additionally, only a small number of shading fabrics were tested and compared. However, as the fabrics selected were considered to be typical of those found in UK domestic and non-domestic buildings, and the fabric of a shading product is the main part of the product that prevents sound from entering or reflecting off hard glazed areas when extended it is felt that these results are indicative of the acoustic performance of internal blinds installed in domestic and non-domestic buildings in the UK.

5.2 Background

5.2.1 Acoustic Comfort within Buildings and Building Regulations

In buildings, upgrading glazing units, installing secondary glazing, and including shutters and heavy curtains are recognised and recommended methods advocated by the building industry to improve the sound insulation properties of a window (Historic England, 2016; Wouter et al., 2010). Improvements in the sound insulation of windows help prevent external noise pollution (e.g., road, aircraft, railway, and pedestrian noise) transmitting through windows into a building. They help keep internal sound power levels (SPL) below < 30 dB in sensitive rooms, i.e., bedrooms, and < 35 dB in less sensitive rooms i.e., living spaces and office spaces. These SPLs are referred to within Approved Document Part F (HM Government, 2013) and are replicated within the UK's devolved administrations. Recommended internal SPLs for other internal spaces are provided in CIBSE Guide A: Environmental Design (2015) and BS 8233 (BSI, 2014).

The uptake of double glazing[44] (for improved energy efficiency) has helped improve the sound insulation properties of windows in the UK although heritage buildings are often unable to install these modern types of glazing (Historic England, 2019). However, increased use of glazing within building design has caused more issues with sound insulation and reverberant sound internally. Glazing units and other lightweight building components provide relatively little sound insulation when compared to the level of sound insulation provided by other materials used in the construction of a façade. This is because of the material properties of the glass and window frames, and varies depending on the quality of the installation (Seguro and Palmer, 2016). The installation of more energy efficient double-glazed units may also require additional ventilation to be incorporated into their design. Trickle vents and openable windows are often relied upon to ensure adequate ventilation is provided for both thermal comfort, in warmer weather, and improvements in

[44]Double glazing is reported to be installed in 85% of homes in England (MHCLG and National Statistics, 2020).

indoor air quality (IAQ). However, opening trickle vents and windows will reduce the sound insulation performance of a window. Therefore, occupants may become conflicted between their need for acoustic comfort and their need for improved thermal comfort and indoor air quality (IAQ) when windows and/or trickle vents are opened (ANC and Institute of Acoustics, 2020; UK Green Building Council, 2016). CIBSE Guide B4 (2016) suggests that as a general guide, a room with a partially open window will experience noise levels which are 10 - 15 dBA below the external noise level.

External noise, sound insulation and the material properties of the facade are not the only aspects that affect internal noise levels. Sound produced internally by occupants or equipment also contributes to increased levels of sound. Open-plan offices, swimming pools and theatres are examples of building types that need to carefully control the amount of reverberant sound within a space. In offices, acoustic comfort is one of the main factors that contribute to occupant dissatisfaction (BCO, 2017). The shift in trends from cellular offices to open-plan office spaces has contributed to an increase in acoustic discomfort in offices (Clements-Croome, 2018; Kim and de Dear, 2013). Two aspects contribute to the total sound level within a room; direct sound (sound that directly comes from the source); and reverberant sound (sound that has been reflected before it is heard by the listener). These vary depending on the size of the room, the distance of the listener from the sound source and the reflectiveness/absorbency of the materials within the room. Rooms with more acoustic absorption decay sound quicker and therefore total sound levels are reduced. The time it takes for sound to decay is called the reverberation time, RT, measured in seconds. An excessively long reverberation time accentuates the background noise and can reduce clarity of speech and cause occupant distractions. However, too short a RT creates a ‘dead room’ which can impede on speech privacy (Peters et al*.,* 2011).

Recommended RTs are not defined in building regulations for residential or non-residential buildings with the exemption of schools where minimum standards are provided by the Department for Education (ANC and Institute of Acoustics, 2020). BB93 Acoustic Design of Schools: performance of schools (DfE, 2015), provides mid-frequency reverberation time, RT_{mf}, for various room types found in schools including offices. The RT_{mf} is the arithmetic average of the reverberation times at 500 Hz, 1 kHz and 2 kHz octave bands, or the arithmetic average of the RT in one-third octave bands from 400 Hz to 2.5 kHz as these frequencies affect speech intelligibility. BB93 recommends that for newly designed offices the RT_{mf} should be ≤ 1 and ≤ 1.2 s in a refurbished office[45]. BS 8233 (BSI, 2014) suggests that the optimum RT will vary depending on whether the room is mainly used for speech or music and provides optimal RTs for both as a function of room volume. The recommended RTs from BS 8233 are listed in Table 44.

Table 44. Optimum reverberation times, RT, for speech and music at 500 Hz dependent on room volume (BSI, 1999).

Room Volume (m^3)	Reverberation Time, RT (s), at 500 Hz	
	Speech	Music
50	0.4	1.0
100	0.5	1.1
200	0.6	1.2
500	0.7	1.3
1000	0.9	1.5
2000	1.0	1.6

The RT of a space can be improved within the structural building design (e.g., through the specification of glazing, ceiling heights, insulation, and flooring) and during the fit-out by integrating the appropriate level of absorptive materials/products into the space (e.g., furniture, carpets, acoustic panels/baffles, inclusion of tensile structures and acoustic curtains). The structural design of buildings often consists of hard, reflective materials such as glass, plaster, and concrete which have low absorption coefficients (α_s) where other softer, more absorbent materials are included within the fit-out/furnishing of a building (Finishes & Interiors Sector, 2015).

5.2.2 Typical Material Performance Values

The sound reduction properties of a building's facade vary depending on the construction. Table 45 provides Sound Reduction Index, R in dB, and the Weighted Sound Reduction, R_w, for typical materials used in the design of buildings in the UK. The higher the R and R_w the greater the sound level reduction and only a $R_w \geq 3$ dB will be perceptible to occupants (Goelzer et al., 2001). The data for glazing, masonry walls, and cavity walls is taken from the supporting documents used to produce BB93 Acoustic Design of Schools: Performance of Schools (DfE, 2015). Additional values for acoustic curtains have been added to Table 45 and these are representative of acoustic curtains that can be opened and closed. Better

[45] Other values are also given for various rooms found commonly in schools (e.g., classrooms, dining room, gymnasium etc) (DfE, 2015).

performing curtains are available although these curtains are not frequently opened and closed. The manufacturers of these vinyl acoustic curtains claim that the weight and tightness of weave dictates the level of sound insulation achievable (Direct Fabrics, 2019).

Table 45. Sound Reduction Index (R) and Weighted Sound Reduction Indices (R_w) of building materials (DfE, 2015; Direct Fabrics, 2019)

Material	Sound Reduction Index, R (dB) in Octave Bands					R_w
	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	
Masonry Wall 200mm lightweight blockwork, fair faced	32	33	41	49	57	40
Masonry Wall 200mm lightweight blockwork, plaster both sides	38	43	49	54	58	48
Masonry Wall 100mm lightweight blockwork, fair faced	39	46	53	57	61	50
Masonry Wall 200mm lightweight blockwork, with plasterboard on dabs both sides	39	50	55	56	60	51
Cavity Wall Two leaves of 100mm dense concrete blocks, 50mm cavity, wall ties, 13mm plaster on both sides	41	49	58	67	75	52
Cavity Wall Two leaves of 280mm brick, 56mm cavity, no ties, outer faces plastered 12mm	48	58	57	77	86	58
Standard Single Glazing 6mm glass in sealed frame	24	30	28	24	28	27
Standard Double Glazing 4/12/4 sealed units	19	29	38	36	38	29
Standard Double Glazing 6/12/6 sealed units	19	29	38	36	45	32
Double Glazing 6/50/6 sealed units	29	34	41	45	53	39
Double Glazing 6/100/6 sound absorptive reveals	35	45	47	48	54	45
Advanced Acoustic Curtains 350 g/m^2 Vinyl	-	-	-	-	-	7
Advanced Acoustic Curtains 610 g/m^2 Vinyl	4.0	6.6	10.3	14.7	19.8	11

Sound Absorption Coefficients, α_s, are on a scale of 1 - 0 with 1 identifying a perfect absorber of sound and 0 providing no absorption of sound. Table 46 provides the Practical Sound Absorption Coefficients, α_{pi}, of common materials used as surface finishes in buildings. The α_{pi} is an average of the Sound Absorption Coefficients, α_s, for each one-third octave band within an octave. The α_{pi} in Table 46 were also taken from the supporting documentation used to produce BB93 Acoustic Design of Schools: Performance of Schools (DfE, 2015). Frequently the Weighted Absorption Coefficient, α_w, of a material or product is also reported however these were not provided as part of the BB93 supporting documentation. Peters et al. (2011) suggests that supplying α_w data alone can be insufficient for acousticians to carry out a detailed acoustic analysis although it is useful for quick product comparisons.

Table 46. Typical Practical Sound Absorption Coefficients of building materials (DfE, 2015)

Material	Practical Absorption Coefficients, α_{pi}, in Octave Bands				
	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Concrete Smooth and painted or glazed	0.01	0.01	0.02	0.02	0.02
Brickwork (Standard)	0.04	0.02	0.04	0.05	0.05
Plasterboard Frame 2 x layers of plasterboard with 50mm mineral wool cavity	0.10	0.06	0.04	0.04	0.05
Slab Flooring Marble or terrazzo	0.01	0.01	0.01	0.02	0.02
Floor Tiles Plastic or linoleum	0.00	0.03	0.00	0.05	0.05
Pile Carpet 9mm tufted, on felt underlay	0.08	0.30	0.60	0.75	0.80
Single Glazing 6mm	0.06	0.04	0.03	0.02	0.02
Double Glazing 2-3mm glass, 10mm air gap	0.05	0.03	0.03	0.02	0.02
Lightweight Curtains 0.2 kg/m2, hung 90mm from wall	0.06	0.39	0.63	0.70	0.73
Heavyweight Curtains 0.5kg/m2, draped to 75% area approx. 130mm from wall, cotton.	0.45	0.65	0.56	0.59	0.71
Acoustic Banner 0.5 kg/m2 wool serge, 100mm from wall	0.40	0.70	0.74	0.88	0.89

In Table 46 it is apparent that a plasterboard frame wall construction provides more absorption than a brick or concrete wall. A pile carpet provides more acoustic absorption than a slab floor/floor tiles and a curtain or an acoustic banner provides more acoustic absorption than a glazed surface. Therefore, hard reflective surfaces are less effective at absorbing sound than softer finishes. The α_{pi} of these harder surfaces - specifically concrete, brickwork, slab flooring, floor tiles, and both single and double glazed surfaces is < 0.10.

5.3 Sound Transmission Performance of Shading Fabrics

For the evaluation of the sound insulation properties of shading fabrics a more exploratory approach was taken within this study. An existing test method, ASTM E2611 - 17 (used to determine the acoustic insulation properties of porous materials), was used to identify the sound reduction performance of the shading fabrics alone. BS EN ISO 717 - 1 (BSI, 2013) was then used to classify the sound reduction performance data which provides a method of calculating the resultant Weighted Sound Reduction, R_w, for each shading fabric tested. These results were then adapted to consider the level of sound reduction achievable when real-world noises are experienced; living activity noise i.e., children playing, termed C (e.g., children playing, railway traffic, motorway road traffic and aeroplane noise at shorter distances), and lower frequency noises, termed C_{tr} (e.g., urban traffic noise, low speed railway noise, pop music and aeroplane noise at large distances). However, the results produced do not consider how the installation or the inclusion of glazing will impact the transmission of sound into a room. Therefore, the sound reduction properties identified only relate to the shading fabric alone and can only be considered indicative of the potential sound reduction that could be perceived by an occupant. Nevertheless, a quicker alternative test method has been identified that could be adopted by manufactures of shading fabrics to better understand the acoustic insulation performance of their shading fabrics which could lead to future innovations in shading fabrics.

5.3.1 Testing Shading Products and Fabrics

BS EN ISO 10140 (BSI, 2016) and ASTM E2611 - 17 testing methods both produce Sound Reduction Indices, R, for each one-third octave band. The former standard produces R indices for a building element/product in situ and the latter for a material alone. To measure the sound insulation properties of building elements in the UK and Europe conventionally BS EN ISO 10140 (BSI, 2016) is used and then results are weighted and adapted for typical types of noise experienced within buildings using BS EN ISO 717 - 1 (BSI, 2013). The testing method differs in BS EN ISO 10140 (BSI, 2016) depending on the type of building element being tested. In general, two either horizontal or vertical chambers are used, each approximately $50m^3$, one is designated the noise source chamber and the other the noise receiving chamber. The test specimen is mounted within the partition between the two chambers. In the noise source chamber, a diffuse sound is produced and emitted by a loudspeaker in multiple positions within the chamber. The average sound pressure levels (SPL) are measured in the noise source and receiving chambers between 100 Hz and 5,000 Hz. The difference in SPLs between the two rooms, the area of the test sample and the sound absorption area in the receiving room are used to produce a R index, in dB, for each one-third octave band frequency[46]. Within the standard it is acknowledged that the acoustic performance of a shading product will also depend on the acoustic performance of the window the blind is fitted to, how the shading product is installed and on the quality of the installation.

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[46] Octave bands divide the audio spectrum into 10 equal parts. The central frequencies of these bands are 31.5 Hz, 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz, 8 kHz, and 16 kHz. One-third octave bands subdivided these into a further 33 bands.

BS EN ISO 10140 (BSI, 2016) is a useful test method for evaluating the impact of building elements on the transmission of sound in real buildings however the methodology has weaknesses which makes it problematic to benchmark the performance of one shading product against another. The size of the window and shading system is specified, and the standard provides six ways in which a shading device can be mounted to the window area. However, the standard provides no specific details on the distances that the shading product should be installed at (e.g., distance the curtain should be from the glazing, or the gaps allowed between the shading curtain and the window reveal). Instead, the standard suggests the installation should be based on real-world practices. This means when testing is carried out the results between different shading products are not likely to be comparable as different parameters may be selected as there is no established 'typical' mounting distance for shading products. Most manufacturers provide recommended mounting distances but in practice the mounting distance is constrained by the design or the façade and consumer preferences. To be able to compare the acoustic performance of shading fabrics produced by different manufacturers each shading product would need to be tested in the same mounting position and at the same distance. A further barrier to the adoption of BS EN ISO 10140 by manufactures of shading products is that the industry produces a large variety of fabrics that vary in material composition, structure, weight, and thickness all of which can be specified to be used in a variety of shading fabric structures (e.g., roller blind, vertical blind, honeycomb blind). This type of testing could be costly to shading manufacturers because of the large number of product variations that would need to be tested to produce a result for every potential installation scenario.

ASTM E2611 - 17 (ASTM International, 2017) provides a cheaper and quicker alternative testing method that yields an equivalent R value for a material. It uses a similar principle to the BS EN ISO 10140 method but instead of measuring the SPL across two rooms a smaller piece of equipment is used called an impedance tube and only a small sample of material is tested. At one end of the tube a sound source is connected, the test specimen is positioned in the centre and between 2 - 4 microphones (positioned with one or two microphones at either side of the test specimen) measure the decay in dB across the material being tested. There are several methods of testing that enable the R to be quantified using an impedance tube and these vary depending on the equipment used (e.g., the number and positioning of microphones) which are referenced within ASTM E2611 - 17. The limitations of this test are that it identifies the acoustic insulation performance of the fabric only, which in a real-world context could alter depending on how the shading product is mounted, the shading product the fabric is used within (i.e., roller blind, vertical blind, honeycomb blind) and the specification and size of the glazing system the shading fabric is installed to. Nevertheless, this method provides a way for shading product manufactures to easily assess the acoustic potential of their fabrics.

5.3.2 Classifying Shading Products and Fabrics

5.3.2.1 Weighted Sound Reduction Index, R_w

R indices data produced from either the BS EN ISO 10140 test method or the ASTM E2611 - 17 can then be simplified using the process outlined in BS EN ISO 717 - 1 (BSI, 2013) to produce a Weighted Sound Reduction Index, R_w. The measured R index for each of the one-third octave bands between 100 and 3150 Hz are compared to the reference curve presented in Figure 107. In Figure 107 the Y-axis presents the reference values (L) in dB and the X-axis identifies the corresponding one-third octave band frequencies (f) in Hz. The shape of the reference curve is based on typical noise spectra experienced in buildings and reflects human hearing sensitivity (Peters et al., 2011)

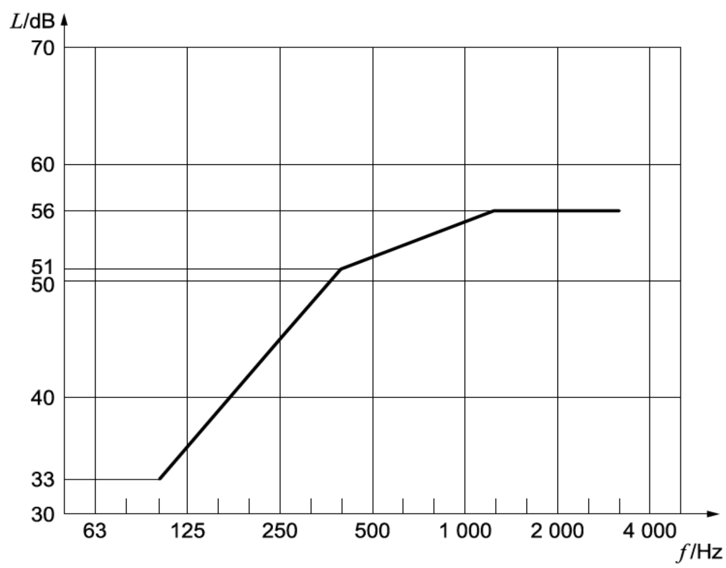


Figure 107. Reference values for the Weighted Sound Reduction Index (BSI, 2013)

This reference curve is then compared to the measured R index curve and shifted by adding a constant number of dB to the reference R index for each one-third octave band until the aggregate of the adverse deviations (or the unfavourable deviations) is as large as possible but no greater than 32 dB. An adverse deviation is a measured R value that is less than the value of the shifted reference curve (i.e., where the measured sound reduction performance has failed to meet the standard set by the reference curve). Positive deviations are considered and noted as a 'PASS' because the measured sound reduction performance has exceeded the standard set by the reference curve. The resultant Weighted Sound Reduction Index, $R_{w,}$ is the shifted value of the reference curve at 500 Hz.

5.3.2.2 Adapting the Weighted Sound Reduction Index, R_w, to consider Living Activity Noise (C) and Traffic Noise (C_{tr})

The Weighted Sound Reduction Index, $R_{w,}$ can then be adapted to consider common types of external noise that penetrate internal spaces. These consider:

- Living activity noise (i.e., higher frequency noises), termed C (e.g., children playing, railway traffic at high and medium speeds, motorway road traffic (< 50 mph) and aeroplane noise at shorter distances)
- Lower frequency noise, termed C_{tr} (e.g., urban traffic noise, low speed railway noise, pop music and aeroplane noise at large distances).

The data outputs from these adaptions of the R_w allow for simpler comparisons to be made between building products or materials which are specific to the type of noise. This is important as not all products and materials are effective in preventing both high and low frequency noise.

The R_w is adapted by applying a correction factor based on the normalised sound level of either living activity noise, C, and lower frequency noise, C_{tr}. The Building Regulations Part E (HM Government, 2010d) specifies the use of the adaptation term C_{tr}.

BS EN ISO 717 - 1 (BSI, 2013) provides the A-weighted sound spectrums for C and C_{tr} in one-third octave bands termed L_{i1} and L_{i2}. This is applied to the R index for each one-third octave band, termed R_i, by subtracting the R_i from the L_{i1} or L_{i2}. These are then summed logarithmically to obtain either X_{A1} or X_{A2} using the following equations:

$$X_{A1} = 10\log\sum(10^{Li1-\frac{Ri}{10}}) \qquad \text{(Equation 8)}$$

$$X_{A2} = 10\log\sum(10^{Li2-\frac{Ri}{10}}) \qquad \text{(Equation 9)}$$

The correction factors, C or C_{tr} is found by subtracting the Weighted Sound Reduction Index, R_w from either X_{A1} or X_{A2} using Equation 10 or 11.

$$C = X_{A1} - R_w \qquad \text{(Equation 10)}$$

$$C_{tr} = X_{A2} - R_w \qquad \text{(Equation 11)}$$

The correction factors are then presented with the R_w in parentheses.

For example: R_w (C; C_{tr}) = 41 (0; -5) dB

To identify the performance of a product or material the R_w is added (arithmetically) to the correction factor, C or C_{tr}. Using the above example, the sound reduction performance of the product or material when there is living activity noise is 41 dB and 36 dB when traffic noise is present.

5.3.3 Methodology

The BS EN ISO 10140 (BSI, 2016) method has some barriers that prevent the acoustic properties of shading fabrics from being compared however the method is essential for accurately predicting the impact they will have on real building as there is flexibility within the standard that allows for a variety of installation scenarios to be tested and considered within the resultant R_w. However, the lack of a test method that can compare the acoustic transmission or insulation performance of a shading fabric against another independent of the shading installation, prohibits fabric manufacturers from identifying the acoustic potential of their fabrics before incorporating them into a shading product and perhaps from carrying out the more robust BS EN ISO 10140 test. Therefore, within this study ASTM E2611 - 17 (using the four-microphone transfer matrix method under two loading conditions) was used to demonstrate how this method could provide quicker and cheaper indicative results of the performance of different shading fabrics typically used in domestic and non-domestic buildings in the UK.

5.3.3.1 Equipment Setup

Two impedance tubes that differed in internal diameter were used to take measurements of high and low incident and reflected sound frequencies. The 100 mm diameter impedance tube is designed to measure frequencies between 63 Hz and 1600 Hz, and the other 30 mm tube is designed to measure frequencies between 800 Hz and 6300 Hz. Figure 108 illustrates the setup for the 100 mm SW-422 impedance tube and Figure 109 identifies the setup for the 30 mm SW-477 impedance tube. Both figures show the distances between microphone positions and the sample surface when setting up the test.

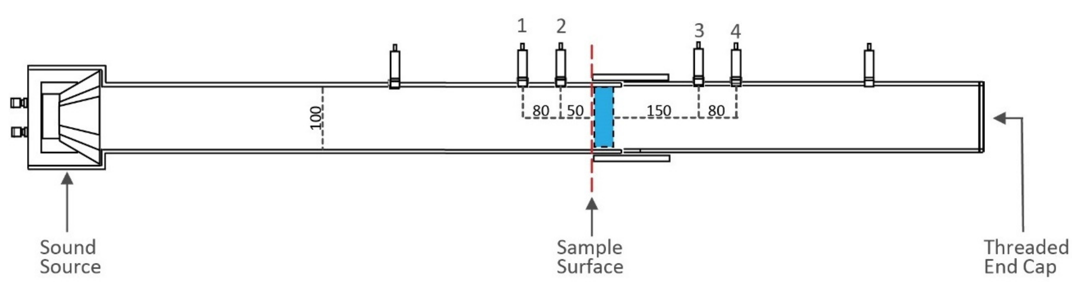


Figure 108.SW-422 100 mm Impedance Tube to measure 63Hz – 1600 Hz sound frequencies. (Items 1,2, 3 and 4 identify the microphone positions and all dimensions are in mm)

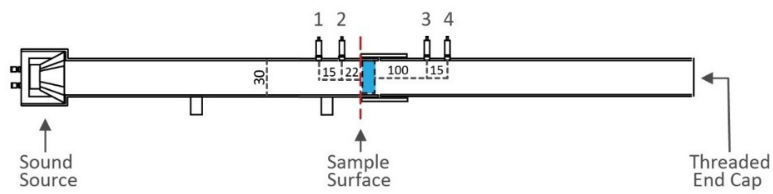


Figure 109. SW-477 30 mm Impedance Tube to measure 800 Hz – 6300 Hz sound frequencies. (Items 1,2, 3 and 4 identify the microphone positions and all dimensions are in mm)

In both instances the microphones are directly connected to a 4-channel MC3242 data acquisition hardware. A PA50 power amplifier was used to drive the sound source in the impedance tube and the BSWA VA-Lab software was used to log and interpret the data collected by the data acquisition hardware.

The two loading conditions used were in accordance with ASTM E2611 - 17:

a. an "anechoic" or otherwise minimally reflecting termination point e.g., the end cap of the impedance tube was in position.

b. an "open termination" reflecting a portion of incident wave e.g., the end cap was removed creating an open termination.

5.3.3.2 Measurements

Environment Conditions:

During the computation of the R indices the software required the Air Temperature (°C), Relative Humidity (%), Air Pressure (Pa) to be measured, recorded, and input into the VA-Lab Software. The air temperature and relative humidity was taken from sensors next to the experiment setup and the air pressure data was taken from an online resource.

Sample Properties:

The sample material thickness was input after measuring each sample in millimetres with a set of Vernier callipers.

5.3.3.3 Data Collection Procedure

Prior to data collection the four microphones that were inserted into the impedance tube were calibrated to 114 dB at 1000 Hz. Calibration was carried out at the start of each testing day.

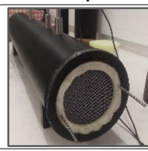
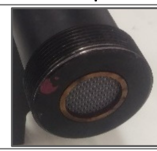
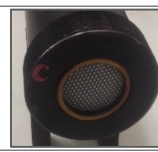
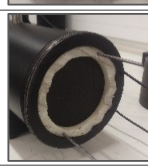
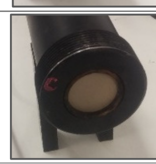
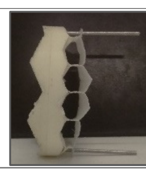
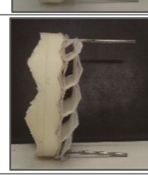
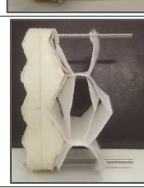
An initial control test was conducted to identify the transmissive properties of the sample holder without the sample to give a control measurement. The same process was followed for all control measurements and sample measurements. The following steps were carried out for each test:

1. The sample holder (with or without sample) was inserted into the impedance tube as shown in Figure 108 and Figure 109.
2. Data relating to the environment conditions, thickness of the material (mm) and the location of the microphones was then input into the data acquisition software and manually recorded by the researcher.
3. The sound source was started which emitted a broadband noise at 94 dB that lasted 20 seconds, whilst the data acquisition software collected the R data.
4. The threaded end cap was removed.
5. Step 3 was repeated.
6. The results for each sample (and empty sample holder) were then averaged to produce the output R data for each one-third octave band frequency between 63 - 6300 Hz.

5.3.3.4 Shading Test Samples

Table 47 shows how each sample was mounted within the two impedance tubes (that had different interior dimensions 30 mm and 100 mm) alongside the material properties, thickness, weight, and structure of each of the fabrics. The size of the samples was dictated by the design of the impedance tube and the sample holder was designed to hold the fabric perpendicular within the tubes.

Table 47. Material properties of samples for transmission testing.

Sample	100mm Sample	Side Profile	30mm Sample	Material	Weight (+/- 5%)	Fabric Structure
A		N/A		42% Fibreglass / 58% PVC	520 g/m^2	Flat
B		N/A		Coated Fibreglass Fabric	430 g/m^2	Flat
C		N/A		36% Fibreglass / 64% PVC	340 g/m^2	Flat
D		N/A		36% Fibreglass / 64% PVC	380 g/m^2	Flat
E		N/A		100% Polyester	260 g/m^2	Flat
F			N/A	100% Polyester	320 g/m^2	Honeycomb
G			N/A	100% Polyester	315 g/m^2	Double Honeycomb
H			N/A	100% Polyester	420 g/m^2	Double Honeycomb

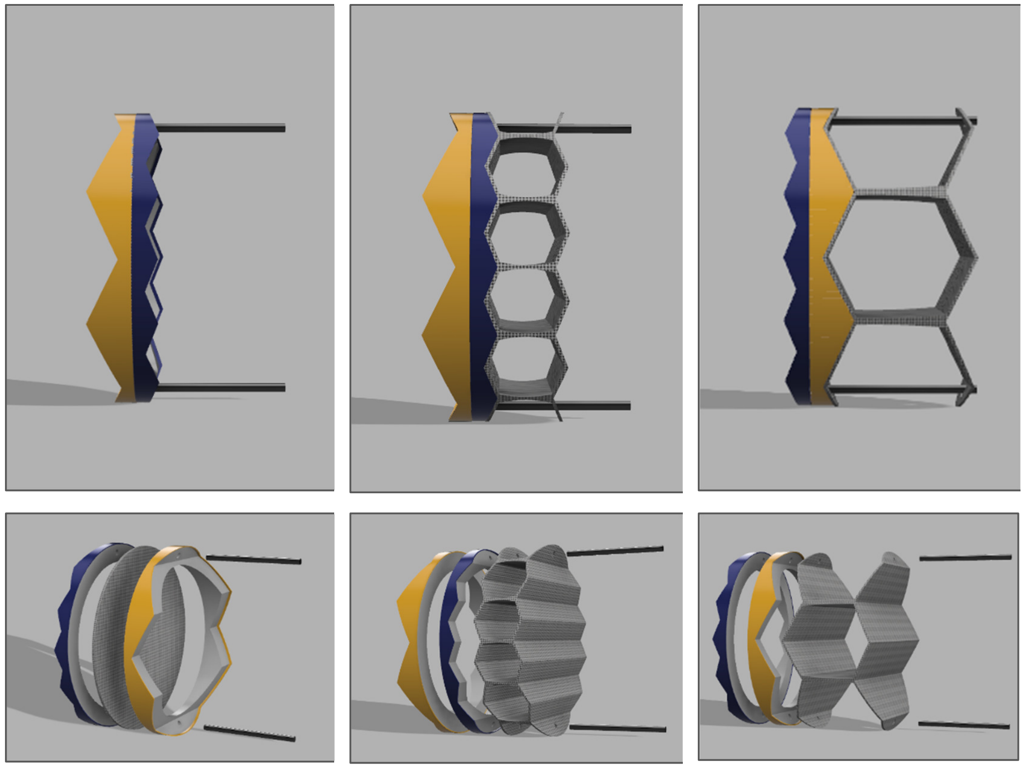
5.3.3.5 Sample Holder Design and Development

Within ASTM E2611 - 17 (ASTM International, 2017) little guidance is given on the sample holder other than that the holder may either be 'integrated with the tube or may be a separate, detachable extension of the tube.' It also states that a circular holder with an airtight fit is used, and this should be placed in the end of the tube opposite the sound source. Therefore, the holder had to conform to the interior shape and dimensions of the main part of the tube. A detachable holder was produced so differing samples could be easily tested.

The differing profile shapes and thicknesses of the fabrics required an adaptable sample holder to be designed and produced (see Table 47). The sample holder needed to be able to hold both the honeycomb and flat fabrics whilst made from the same density and volume of material so comparisons could be made between samples. For the larger diameter tube (100 mm) this was created by 3D printing a sample holder. However, for the smaller tube it was not possible to design a holder that would effectively hold the honeycomb structured test samples (Samples F, G and H). An alternative MDF 3 mm laser cut holder was produced for the flat sample fabrics to be used within the 30 mm impedance tube. This meant that R data related to 100 - 6300 Hz could be collected for the 'flat' fabrics where only 63 - 1600 Hz data could be collected for the 'honeycomb' structures.

Design and development of 3D printed 100 mm sample holder

To develop the 3D printed holder the profile shape of each of the honeycomb structures (32 mm and 64 mm in width) was assessed and incorporated into the design. The holder was constructed of two detachable elements that snap fitted into one another. The centre of the holder was designed to hold flat fabrics up to 1 mm in thickness. The front and back face of the holder could be applied with an adhesive and two short (8 cm) metal rods slotted through the top and bottom of the fabric sample to hold the sample in tension to produce the honeycomb shape. Figure 110 shows a CAD visual of the sample holder produced with the varying three structures of the sample in place.



Flat Fabric *32 mm Honeycomb* *64 mm Honeycomb*

Figure 110. Side and exploded view of 100 mm sample holder with test samples.

<u>Design and development of 30mm MDF sample holder</u>

The laser cut holder was made of two pieces of circular 3 mm MDF with an outer diameter of 30 mm and an inner cut out diameter of 25 mm. The fabric was cut to a 30 mm diameter and sandwiched (with adhesive) between the two circular frames as shown in Figure 111.

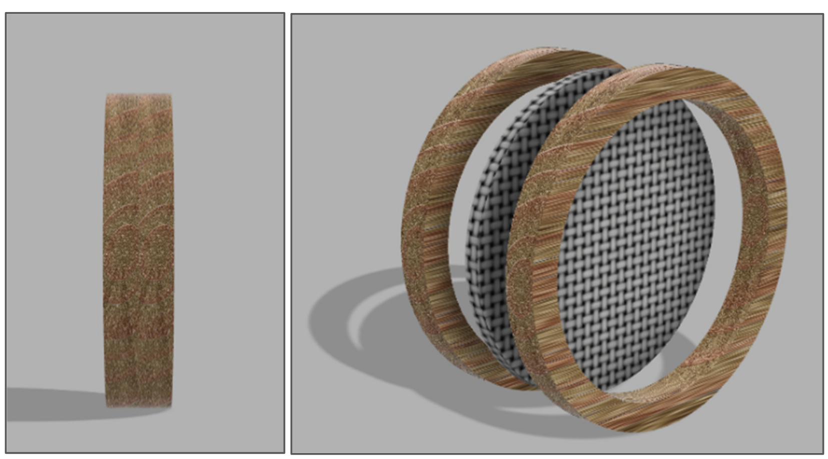


Figure 111. Side and exploded view of 30mm sample holder setup for flat fabrics.

5.3.4 Analysis and Results

5.3.4.1 Sound Reduction Index (R)

The equipment was set up for the 100 mm impedance tube to output the R indices for frequencies between 63 - 1600 Hz and the 30 mm impedance tube for 2000 and 6300 Hz. Samples A - E were tested in both the 30 and 100 mm impedance tubes resulting in R indices for 63 - 6300 Hz in one-third octave bands whilst Samples F - H were only possible to test in the larger impedance tube resulting in R indices for one-third octave bands between 63 - 1600 Hz. Both sample holders were tested without fabrics installed to identify whether the sample holder had an impact on the transmission of sound recorded. The R indices from the data acquisition software for each sample were then reviewed.

5.3.4.1.1 Sound Reduction Index of the Sample Holders

Figure 112 identifies the R for the sample holders alone. This impact was relatively low with the holder accounting for less than 0.8 dB across all frequencies.

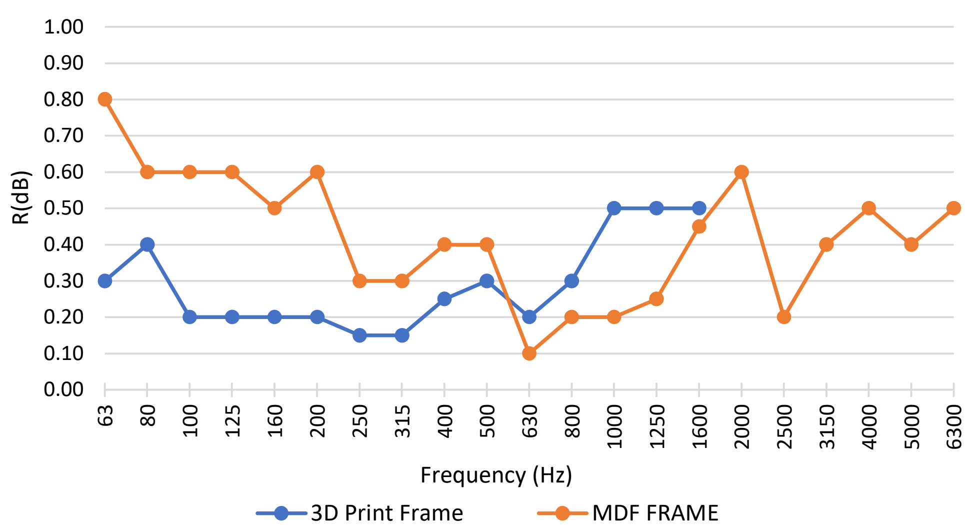


Figure 112. Sound Reduction Index, R (dB) for 3D printed and MDF sample holder.

5.3.4.1.2 Sound Reduction Index (R) of the Samples

Figure 113 presents the R indices for each one-third octave band between 63 Hz - 6300 Hz for the samples tested.

- Samples A, C, D and F provided very little sound reduction < 3 dB. This level of sound reduction would be unidentifiable by a person (Goelzer et al., 2001);
- Sample B, E, G and H reduced sound transmission by > 3 dB for certain frequencies, suggesting that the level of sound reduction provided by these

shading fabrics would be perceived by a person for certain frequencies of sound.

Figure 113 also identifies that:

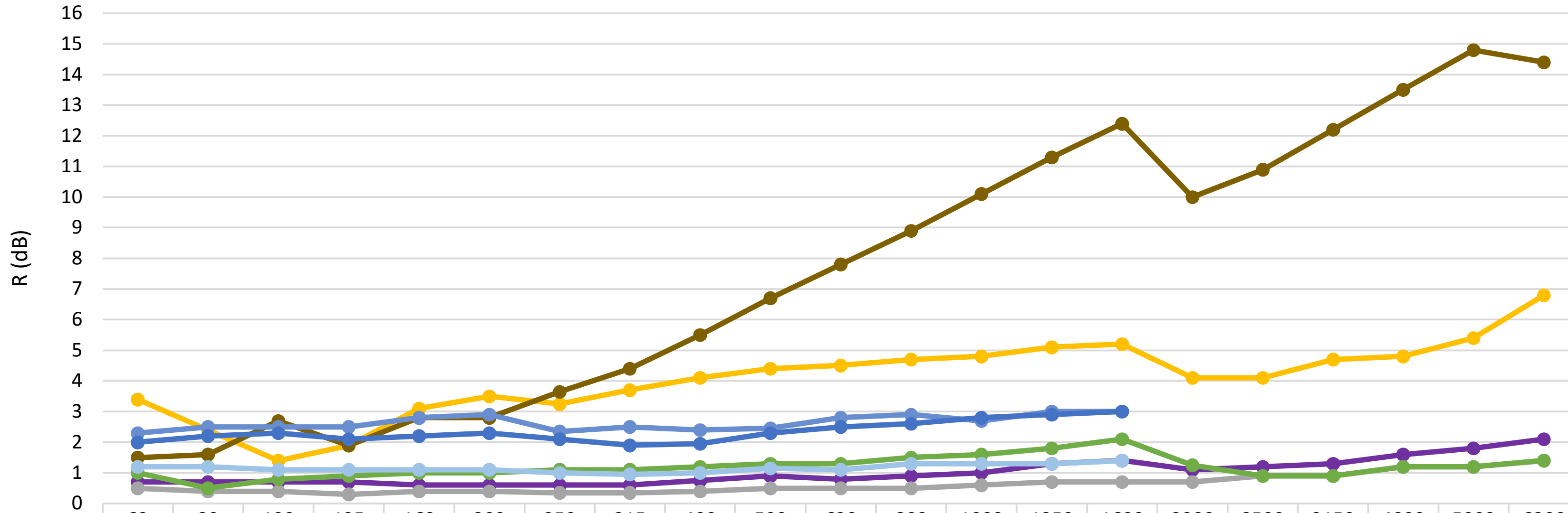
- For low frequencies (63 - 250 Hz) of sound Sample B and G were the best performing.
- For all other frequencies (250 Hz - 6300 Hz) of sound Sample E was best performing.

However, as Samples F - H (the honeycomb fabrics) were not tested for their performance between 2000 Hz - 6300 Hz we cannot be certain of their performance.

When analysing the fabrics that reduced sound by > 3 dB and how they affected the frequencies that affect speech (250 - 5000 Hz for the flat fabrics and 250 - 1600 Hz for the structured fabrics). It is observed that:

- Samples A, C, D & F reduced sound by < 2 dB between 250 Hz - 5000 Hz with the mid-frequency one-third octave band (1000 Hz) achieving ≤ 1.6 dB reduction which would not be noticeable by an occupant (Goelzer et al., 2001).
- Sample B reduced sound by 3 - 5 dB between 250 Hz - 5000 Hz with the mid-frequency one-third octave band (1000 Hz) achieving a 5 dB reduction in sound. If provided, this level of sound reduction would be 'just perceptible' or 'clearly noticeable' by an occupant (Goelzer et al., 2001).
- Sample E reduced sound by 4 - 15 dB between 250 Hz - 5000 Hz with the mid-frequency one-third octave band (1000 Hz) achieving a 10 dB reduction in sound. If provided, this level of sound reduction would be 'clearly noticeable' or equivalent to the halving of sound perceived by an occupant (Goelzer et al., 2001).
- Both Sample G and H reduced sound between 2 - 3 dB between 250 Hz - 1600 Hz with the mid-frequency one-third octave band (1000 Hz) achieving a 2.7 - 2.8 dB reduction in sound which suggests that the level of sound reduction would be almost 'just perceptible' by an occupant (Goelzer et al., 2001).

When comparing the way structured and flat fabrics performed it is observed that the structured fabrics performed more consistently across the frequency bands than the flat fabrics. The flat fabric's level of sound reduction fluctuated across the frequency bands with higher sound reduction levels being related to higher frequency bands.



	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300
Sample A	0.70	0.70	0.70	0.70	0.60	0.60	0.60	0.60	0.75	0.90	0.80	0.90	1.00	1.30	1.40	1.10	1.20	1.30	1.60	1.80	2.10
Sample B	3.40	2.40	1.40	1.90	3.10	3.50	3.25	3.70	4.10	4.40	4.50	4.70	4.80	5.10	5.20	4.10	4.10	4.70	4.80	5.40	6.80
Sample C	0.50	0.40	0.40	0.30	0.40	0.40	0.35	0.35	0.40	0.50	0.50	0.50	0.60	0.70	0.70	0.70	0.90	0.90	1.20	1.20	1.40
Sample D	1.00	0.50	0.80	0.90	1.00	1.00	1.10	1.10	1.20	1.30	1.30	1.50	1.60	1.80	2.10	1.25	0.90	0.90	1.20	1.20	1.40
Sample E	1.50	1.60	2.70	1.90	2.80	2.80	3.65	4.40	5.50	6.70	7.80	8.90	10.10	11.30	12.40	10.00	10.90	12.20	13.50	14.80	14.40
Sample F	1.20	1.20	1.10	1.10	1.10	1.10	1.00	0.95	1.00	1.15	1.10	1.30	1.30	1.30	1.40	—	—	—	—	—	—
Sample G	2.30	2.50	2.50	2.50	2.80	2.90	2.35	2.50	2.40	2.45	2.80	2.90	2.70	3.00	3.00	—	—	—	—	—	—
Sample H	2.00	2.20	2.30	2.10	2.20	2.30	2.10	1.90	1.95	2.30	2.50	2.60	2.80	2.90	3.00	—	—	—	—	—	—

Frequency (Hz)

Figure 113. Sound Reduction, R, (dB) for all samples and frequencies measured (Flat Fabrics, Samples A - H, measured across 63 - 6300 Hz and Structured Fabrics, Samples F - H, measured across 63 - 1600 Hz). Frequencies between 250 Hz and 5000 Hz affect speech (Peters et al., 2011).

5.3.4.2 Weighted Sound Reduction Index (R_w)

Table 48 presents the Weighted Sound Reduction Index, R_w, for each. To calculate the, R_w, the R index for each one-third octave band was used with the methodology explained in BS EN ISO 717 - 1 (BSI, 2013) and briefly described in Section 5.3.2.1 (p. 310).

Table 48. Weighted Sound Reduction Index, R_w for the flat fabric samples tested and evaluated.

Sample	R_w (dB)
A	1
B	5
C	1
D	2
E	10

To calculate the R_w the R indices for 100 - 3150 Hz are required. Therefore, only the flat fabrics (Sample A - E) were possible to evaluate the R_w for. Table 49 - Table 53 identify the shift in dB to the reference curve and the resulting R_w for each sample based on the aggregate of the adverse deviations (AAD) which could not exceed 32 dB. Within these tables a ‘PASS’ represents a positive deviation from the reference curve i.e., the sound reduction performance has exceeded the standard set by the reference curve. In each of the tables the row highlighted in grey shows the results for 500 Hz and the result in bold highlights the R_w result where the AAD did not exceed 32 dB.

Like the results of the R indices, Sample E (100% polyester, 260 g/m^2) had the largest R_w, at 10 dB, followed by Sample B (Coated Fibreglass, 430 g/m^2) at 5 dB. The remaining samples had a R_w of < 3 dB, which would be unidentifiable by a person (Goelzer et al., 2001).

Table 49. Sample A calculation of the Weighted Sound Reduction Index, R_w.

			1st Try		2nd Try		3rd Try	
Frequency (Hz)	Measured R Index (dB)	Reference Values as per BS EN ISO 717 (dB)	Reference Values shifted by 49 dB	Adverse Deviations (dB)	Reference Values Shifted by 50 dB	Adverse Deviations (dB)	Reference Values Shifted by 51 dB	Adverse Deviations (dB)
100	0.70	33	-16	PASS	-17	PASS	-18	PASS
125	0.70	36	-13	PASS	-14	PASS	-15	PASS
160	0.60	39	-10	PASS	-11	PASS	-12	PASS
200	0.60	42	-7	PASS	-8	PASS	-9	PASS
250	0.60	45	-4	PASS	-5	PASS	-6	PASS
315	0.60	48	-1	PASS	-2	PASS	-3	PASS
400	0.75	51	2	1.3	1	0.3	0	PASS
500	0.90	52	3	2.1	2	1.1	1	0.1
630	0.80	53	4	3.2	3	2.2	2	1.2
800	0.90	54	5	4.1	4	3.1	3	2.1
1000	1.00	55	6	5.0	5	4.0	4	3.0
1250	1.30	56	7	5.7	6	4.7	5	3.7
1600	1.40	56	7	5.6	6	4.6	5	3.6
2000	1.10	56	7	5.9	6	4.9	5	3.9
2500	1.20	56	7	5.8	6	4.8	5	3.8
3150	1.30	56	7	5.7	6	4.7	5	3.7
Aggregate of Adverse Deviation (AAD) =				44.4 dB		34.4 dB		25.1 dB
			R_w =	1 dB				

Table 50. Sample B calculation of the Weighted Sound Reduction Index, R_w.

			1st Try		2nd Try		3rd Try	
Frequency (Hz)	Measured R Index (dB)	Reference Values as per BS EN ISO 717 (dB)	Reference Values Shifted by 46 dB	Adverse Deviations (dB)	Reference Values Shifted by 47 dB	Adverse Deviations (dB)	Reference Values Shifted by 48 dB	Adverse Deviations (dB)
100	1.40	33	-13	PASS	-14	PASS	-15	PASS
125	1.90	36	-10	PASS	-11	PASS	-12	PASS
160	3.10	39	-7	PASS	-8	PASS	-9	PASS
200	3.50	42	-4	PASS	-5	PASS	-6	PASS
250	3.25	45	-1	PASS	-2	PASS	-3	PASS
315	3.70	48	2	-1.7	1	PASS	0	PASS
400	4.10	51	5	0.9	4	PASS	3	PASS
500	4.40	52	6	1.6	**5**	0.6	4	PASS
630	4.50	53	7	2.5	6	1.5	5	0.5
800	4.70	54	8	3.3	7	2.3	6	1.3
1000	4.80	55	9	4.2	8	3.2	7	2.2
1250	5.10	56	10	4.9	9	3.9	8	2.9
1600	5.20	56	10	4.8	9	3.8	8	2.8
2000	4.10	56	10	5.9	9	4.9	8	3.9
2500	4.10	56	10	5.9	9	4.9	8	3.9
3150	4.70	56	10	5.3	9	4.3	8	3.3
Aggregate of Adverse Deviation (AAD) =				37.6 dB		29.4 dB		20.8 dB
			R_w =	5 dB				

Table 51. Sample C calculation of the Weighted Sound Reduction Index, R_w.

			1st Try		2nd Try		3rd Try	
Frequency (Hz)	Measured R Index (dB)	Reference Values as per BS EN ISO 717 (dB)	Reference Values Shifted by 50 dB	Adverse Deviations (dB)	Reference Values Shifted by 51 dB	Adverse Deviations (dB)	Reference Values Shifted by 52 dB	Adverse Deviations (dB)
100	0.40	33	-17	PASS	-18	PASS	-19	PASS
125	0.30	36	-14	PASS	-15	PASS	-16	PASS
160	0.40	39	-11	PASS	-12	PASS	-13	PASS
200	0.40	42	-8	PASS	-9	PASS	-10	PASS
250	0.35	45	-5	PASS	-6	PASS	-7	PASS
315	0.35	48	-2	PASS	-3	PASS	-4	PASS
400	0.40	51	1	0.6	0	PASS	-1	PASS
500	0.50	52	2	1.5	**1**	0.5	0	PASS
630	0.50	53	3	2.5	2	1.5	1	0.5
800	0.50	54	4	3.5	3	2.5	2	1.5
1000	0.60	55	5	4.4	4	3.4	3	2.4
1250	0.70	56	6	5.3	5	4.3	4	3.3
1600	0.70	56	6	5.3	5	4.3	4	3.3
2000	0.70	56	6	5.3	5	4.3	4	3.3
2500	0.90	56	6	5.1	5	4.1	4	3.1
3150	0.90	56	6	5.1	5	4.1	4	3.1
Aggregate of Adverse Deviation (AAD) =				38.6 dB		29.0 dB		20.5 dB
			R_w =	**1 dB**				

Table 52. Sample D calculation of the Weighted Sound Reduction Index, R_w.

			1st Try		2nd Try		3rd Try	
Frequency (Hz)	Measured R Index (dB)	Reference Values as per BS EN ISO 717 (dB)	Reference Values Shifted by 49 dB	Adverse Deviations (dB)	Reference Values Shifted by 50 dB	Adverse Deviations (dB)	Reference Values Shifted by 51 dB	Adverse Deviations (dB)
100	0.80	33	-16	PASS	-17	PASS	-18	PASS
125	0.90	36	-13	PASS	-14	PASS	-15	PASS
160	1.00	39	-10	PASS	-11	PASS	-12	PASS
200	1.00	42	-7	PASS	-8	PASS	-9	PASS
250	1.10	45	-4	PASS	-5	PASS	-6	PASS
315	1.10	48	-1	PASS	-2	PASS	-3	PASS
400	1.20	51	2	0.8	1	PASS	0	PASS
500	1.30	52	3	1.7	**2**	0.7	1	PASS
630	1.30	53	4	2.7	3	1.7	2	0.7
800	1.50	54	5	3.5	4	2.5	3	1.5
1000	1.60	55	6	4.4	5	3.4	4	2.4
1250	1.80	56	7	5.2	6	4.2	5	3.2
1600	2.10	56	7	4.9	6	3.9	5	2.9
2000	1.25	56	7	5.8	6	4.8	5	3.8
2500	0.90	56	7	6.1	6	5.1	5	4.1
3150	0.90	56	7	6.1	6	5.1	5	4.1
	Aggregate of Adverse Deviation (AAD) =			41.2 dB		31.4 dB		22.7 dB
			R_w =	2 dB				

Table 53. Sample E calculation of the Weighted Sound Reduction Index, R_w.

			1st Try		2nd Try		3rd Try	
Frequency (Hz)	Measured R Index (dB)	Reference Values as per BS EN ISO 717 (dB)	Reference Values Shifted by 41 dB	Adverse Deviations (dB)	Reference Values Shifted by 42 dB	Adverse Deviations (dB)	Reference Values Shifted by 43 dB	Adverse Deviations (dB)
100	2.7	33	-8	PASS	-9	PASS	-10	PASS
125	1.9	36	-5	PASS	-6	PASS	-7	PASS
160	2.8	39	-2	PASS	-3	PASS	-4	PASS
200	2.8	42	1	PASS	0	PASS	-1	PASS
250	3.7	45	4	0.4	3	PASS	2	PASS
315	4.4	48	7	2.6	6	1.6	5	0.6
400	5.5	51	10	4.5	9	3.5	8	2.5
500	6.7	52	11	4.3	10	3.3	9	2.3
630	7.8	53	12	4.2	11	3.2	10	2.2
800	8.9	54	13	4.1	12	3.1	11	2.1
1000	10.1	55	14	3.9	13	2.9	12	1.9
1250	11.3	56	15	3.7	14	2.7	13	1.7
1600	12.4	56	15	2.6	14	1.6	13	0.6
2000	10.0	56	15	5.0	14	4.0	13	3.0
2500	10.9	56	15	4.1	14	3.1	13	2.1
3150	12.2	56	15	2.8	14	1.8	13	0.8
Aggregate of Adverse Deviation (AAD) =				42.2 dB		30.8 dB		19.8 dB
			R_w =	10 dB				

5.3.4.3 Adapted R_w for Living Activity Noise (C) and Traffic Noise (C_{tr})

For the two fabrics that had a $R_w > 3$ dB (Sample B and E) the correction factors C and C_{tr} were calculated to identify how the R_w would be modified if living activity noises (i.e., high frequency sound) or traffic noise (i.e., low frequency sound) were present. This process is outlined in BS EN ISO 717 - 1 (BSI, 2013) and was briefly described in Section 5.3.2.2 (p. 311).

The C and C_{tr} for Sample B and E are presented in Table 55 and Table 56 on the following pages. These tables also show how the C and C_{tr} were calculated for each of the samples. These correction factors and resultant adapted R_w are summarised in Table 54.

Table 54. R_w and adapted R_w for Living Activity Noise (C) and Traffic Noise (C_{tr})

Sample	R_w (dB)	R_w (C, C_{tr})	R_w + C	R_w + C_{tr}
A	1	-	-	-
B	5	5 (0; -1)	5	4
C	1	-	-	-
D	2	-	-	-
E	10	10 (-1; -2)	9	8

When adjusting Sample B for:

- Living Activity Noise (or high frequency noise), C, Sample B required a R_w correction of 0 dB, resulting in an adapted R_w of 5 dB.
- Traffic Noise (or low frequency noise), C_{tr}, a R_w correction of -1 dB was calculated resulting in an adapted R_w of 4 dB.

When adjusting Sample E for:

- Living Activity Noise (or high frequency noise), C, Sample E required a R_w correction of -1 dB, resulting in an adapted R_w of 9 dB.
- Traffic Noise (or low frequency noise), C_{tr}, a R_w correction of -2 dB was calculated resulting in an adapted R_w of 8 dB.

For both fabrics, a larger correction factor was calculated for traffic noise (low frequency noise), C_{tr}, than living activity noise (high frequency noise), C. This relates to the shading fabrics R performance which identified that both fabrics reduced high frequency noise better than low frequency noise.

Table 55. Sample B adaption of R_w for Living Activity Noise (C) and Traffic Noise (C_{tr})

Frequency (Hz)	R for Sample B (R_i, dB)	Reference values shifted by 42dB	Adverse Deviation (dB)	C Spectrum	$L_{i1} - R_i$	$10^{(Li1 - Ri)/10}$ (dB x 10^{-5})	C_{tr} Spectrum	$L_{i2} - R_i$	$10^{(Li2 - Ri)/10}$ (dB x 10^{-5})
100	1.4	-14	PASS	-29	-30	91.20	-20	-21	724.44
125	1.9	-11	PASS	-26	-28	162.18	-20	-22	645.65
160	3.1	-8	PASS	-23	-26	245.47	-18	-21	776.25
200	3.5	-5	PASS	-21	-25	354.81	-16	-20	1122.02
250	3.3	-2	PASS	-19	-22	595.66	-15	-18	1496.24
315	3.7	1	PASS	-17	-21	851.14	-14	-18	1698.24
400	4.1	4	PASS	-15	-19	1230.27	-13	-17	1949.84
500	4.4	5	0.6	-13	-17	1819.70	-12	-16	2290.87
630	4.5	6	1.5	-12	-17	2238.72	-11	-16	2818.38
800	4.7	7	2.3	-11	-16	2691.53	-9	-14	4265.80
1000	4.8	8	3.2	-10	-15	3311.31	-8	-13	5248.07
1250	5.1	9	3.9	-9	-14	3890.45	-9	-14	3890.45
1600	5.2	9	3.8	-9	-14	3801.89	-10	-15	3019.95
2000	4.1	9	4.9	-9	-13	4897.79	-11	-15	3090.30
2500	4.1	9	4.9	-9	-13	4897.79	-13	-17	1949.84
3150	4.7	9	4.3	-9	-14	4265.80	-15	-20	1071.52
R_w (dB at 500Hz) =		5			SUM =	35345.72 x 10^{-5}		SUM =	36057.86 x 10^{-5}
R_w (C, C_{tr}) =		5 (0; -1) dB			X_{A1} =	-10log (35345.72 x 10^{-5})		X_{A2} =	-10log (36057.86 x 10^{-5})
					X_{A1} =	4.52		X_{A2} =	4.43
					C =	$X_{A1} - R_w$ = 4.52 - 5		C =	$X_{A1} - R_w$ = 4.43 - 5
					C =	**0**		**C_{tr} =**	**-1**

Table 56. Sample E adaption of R_w for Living Activity Noise (C) and Traffic Noise (C_{tr})

Frequency (Hz)	R for Sample E (R_i, dB)	Reference values shifted by 42dB	Adverse Deviation (dB)	C Spectrum	$L_{i1} - R_i$	$10^{(Li1 - Ri)/10}$ (dB x 10^{-5})	C_{tr} Spectrum	$L_{i2} - R_i$	$10^{(Li2 - Ri)/10}$ (dB x 10^{-5})
100	2.7	-9	PASS	-29	-32	67.61	-20	-23	537.03
125	1.9	-6	PASS	-26	-28	162.18	-20	-22	645.65
160	2.8	-3	PASS	-23	-26	263.03	-18	-21	831.76
200	2.8	0	PASS	-21	-24	416.87	-16	-19	1318.26
250	3.7	3	PASS	-19	-23	543.25	-15	-19	1364.58
315	4.4	6	1.6	-17	-21	724.44	-14	-18	1445.44
400	5.5	9	3.5	-15	-21	891.25	-13	-19	1412.54
500	6.7	10	3.3	-13	-20	1071.52	-12	-19	1348.96
630	7.8	11	3.2	-12	-20	1047.13	-11	-19	1318.26
800	8.9	12	3.1	-11	-20	1023.29	-9	-18	1621.81
1000	10.1	13	2.9	-10	-20	977.24	-8	-18	1548.82
1250	11.3	14	2.7	-9	-20	933.25	-9	-20	933.25
1600	12.4	14	1.6	-9	-21	724.44	-10	-22	575.44
2000	10.0	14	4	-9	-19	1258.93	-11	-21	794.33
2500	10.9	14	3.1	-9	-20	1023.29	-13	-24	407.38
3150	12.2	14	1.8	-9	-21	758.58	-15	-27	190.55

R_w (dB at 500Hz) =	10
R_w (C, C_{tr}) =	10 (-1; -2) dB

SUM =	11886.29 x 10^{-5}	SUM =	16294.06 x 10^{-5}
X_{A1} =	-10log (11886.29 x 10^{-5})	X_{A2} =	-10log (16294.06 x 10^{-5})
X_{A1} =	9.25	X_{A2} =	7.87
C =	$X_{A1} - R_w$ = 9.25 - 10	C =	$X_{A1} - R_w$ = 7.87 - 10
C =	**-1**	**C_{tr} =**	**-2**

5.3.5 Discussion

When carrying out the method outlined in ASTM E2611 - 17 (ASTM International, 2017) it was identified that additional guidance needs to be provided regarding how the fabrics should be held within the impedance tube and a method should be formulated that can also apply to different structured fabrics. A custom-made holder was created in this study, but the researcher was still unable to apply the same method to the smaller impedance tube due to the small diameter (30 mm) and circular shape of the impedance tube. This meant it was not possible to measure the sound reduction performance of the structured fabrics for sound frequencies between 1600 - 6300 Hz thus the researcher was unable to apply the BS EN ISO 717 - 1 method for calculating the R_w and the adapted values for C and C_{tr}. The development of a larger impedance tube (that is ideally square or rectangular in shape) would be beneficial for manufacturers of shading fabrics as the shape and size of tube would be more suited to mounting shading fabrics of differing structures. Alternatively, the existing BS EN ISO 10140 could be used if a standardised testing approach was identified for the purposes of benchmarking the acoustic insulation properties of shading fabrics (BSI, 2016). Whilst it was known at the outset of this study that it would not be possible to identify the R_w for the structured fabrics, flat fabrics (which are more commonly installed in the UK) were able to be tested and compared.

The shading fabrics used within this study varied in weight, material composition, weave and structure and therefore had differing visual and thermal characteristics. Generally, products that were opaquer and made of polyester performed better within the transmission tests apart from Sample B. Sample B was made from a 'coated fibreglass' and was lighter than the majority of the polyester fabrics tested. Polyester, opaque shading fabrics are more typically found within residential bedrooms where external noise and light may disturb occupants sleeping. Sample Bs good performance suggests that it is not only the materials composition but also the structure of the weave of the fabric that contributes to the acoustic transmission properties.

It was surprising to find that Sample E (a flat, polyester fabric) performed significantly better than the other structured polyester fabrics in attenuating sound. The structured fabric design provides an air pocket which is known to improve acoustic attenuation, like that of double or secondary glazing (Garg et al., 2012). However, unlike a glazing construction the air pocket in the shading fabrics tested were not sealed. A better performance may have been achieved if the air pocket was sealed or semi-sealed. For example, if the shading product was installed to the window within a frame a better sound attenuation performance may have been achieved. Sample E's good performance contradicts the findings of Matos and Carvalho (2010) who concluded that a heavier and denser fabric attenuated sound more effectively. Sample E was the lightest fabric tested and was one of the best fabrics for attenuating sound achieving a R_w = 10 dB at 500 Hz. However, as the material compositions were not fully described within the work of Matos and Carvalho (2010) and no other 100% polyester flat fabric was tested in this study, conclusions are difficult to make as to why Sample E performed well. The researcher hypothesises that the fibrous finish of the Sample E fabric contributed to its good performance as this finish increases the surface area of the material and it was the only fabric to have this type of finish. In future work the surface finish, structure of the weave, and air layers should be considered in identifying how well shading fabrics perform.

Overall, the fabrics tested were more beneficial at reducing higher frequencies of sound as opposed to lower frequencies of sound. When considering how the fabrics affected the frequencies that alter speech intelligibility (200 - 5000 Hz), Sample E was most beneficial and reduced sound levels by 9 dB on average. Sample B and G were slightly more beneficial than Sample E at reducing low frequency sound between (63 - 250 Hz) but on average still provided < 3 dB reduction in sound.

When considering the calculated R_w and the corrected values for living activity (C) and traffic noise (C_{tr}), three of the five fabrics produced a R_w < 2 dB which would not make a noticeable difference to an occupant's perception of the sound levels. These results are similar to the extent of the sound reduction identified by the shading products tested by Matos and Carvalho (2010), who identified a < 3 dB reduction in R_w when differing shading fabrics were installed internally on a window using a testing method similar to the one described in BS EN ISO 10140 (BSI, 2016). The two remaining fabrics (Samples B and E) tested in this study identified a R_w of 5 (C 0; C_{tr} -1) dB and 10 (C -1; C_{tr} -2) dB, respectively. This suggests that the level of sound reduction provided by Sample B would be perceived as clearly noticeable and sound passing through Sample E would be perceived as half as loud to an occupant (Goelzer et al., 2001). Additionally, when considering the correction factors for living activity, C, and traffic noise, C_{tr}, Sample B and Sample E would still provide a noticeable reduction in sound levels. However, as the test methods used to identify the R_w in this study and the study of Matos and Carvalho (2010), differ no robust conclusions can be drawn.

The limitation of this testing method is that it only provides data regarding the combined properties of a shading fabric and the benefits and disadvantages of each property (i.e., material, weave, structure, weight, surface area, and openness of the fabric) can only be identified if further systematic testing of shading fabrics is done using the same testing method. Furthermore, it has been highlighted in previous research that the installation of the product system and the size of the window area influences the sound attenuation of shading devices and only testing to BS EN ISO 10140 (BSI, 2016) will identify how these factors influence the sound reduction properties of the overall shading system.

5.4 Sound Absorption Performance of Shading Fabrics

To measure the absorptive properties of various shading products the test method outlined in BS EN ISO 354 (BSI, 2003) was followed. The method specifies that shading products should be tested at a mounting distance of 100 mm and additional distances of integral multiples of 50 mm can be tested. The intent of this guidance is to allow real-world conditions to be simulated but also allows for all shading product data to be compared. In practice the installation and position of shading devices varies depending on the requirements of the consumer generally for aesthetic reasons or because the building design constrains the way the shading product can be installed. In view of this, different mounting distances from the glazing were considered within the test method outlined by BS EN ISO 354 (BSI, 2003) to better understand the absorptive performance of shading products when installed at different distances from the glazing. BS EN ISO 11654 (BSI, 1997) was then used to simplify and classify the acoustic absorption data to provide a Practical Sound Absorption Coefficient, α_{pi}, for each octave band and an overall Weighted Absorption Coefficient, α_w. The α_{pi} and the α_w were then used in acoustic design calculations used by acousticians to predict the reverberation time (RT) of any given room. Within this study the RT of the case study office examined in Chapter 4 was theoretically calculated to identify how including an internal shading product would alter the RT of the office. The office used in Chapter 4 is considered representative of a typical office in the UK.

5.4.1 Methodology

5.4.1.1 Testing and Classifying Shading Products

5.4.1.1.1 Sound Absorption Coefficient, α_s.

BS EN ISO 354 (BSI, 2003) provides guidance on how to mount and test differing products (including window blinds, curtain fabrics, plaster, acoustic baffles, products that are glued to hard surfaces and products that hang with air space either side) for their acoustic absorption properties. The sound absorption coefficient, α_s, of 1 identifies a perfect absorber and 0 offers no sound absorption. The test requires a test sample to be placed/installed within a reverberation chamber with two calibrated microphones and either one or two sound sources. For internal shading products that are positioned vertical to the window the procedure for Type G Mounting should be followed (BSI, 2003). For this, the shading product is installed and hung parallel to a vertical surface within the reverberation chamber and 100 mm is measured between the face of the test specimen and the room surface. As previously mentioned further distances of integral multiples of 50 mm can be optionally tested.

Once installed the reverberation chamber is sealed, and the sound source produces a broadband noise until the Sound Power Level (SPL), measured in dB, reaches a stationary average. The sound source is then stopped, and the time taken (in seconds) for sound to decay by 60 dB across one-third octave band frequencies (between 100 Hz and 5,000 Hz) is measured. The same test is then carried out both with and without the product or test sample within the room. The sound absorption area of the room with the sample, termed A_1, and without the sample, termed A_2, is calculated using Equation 12 (Peters et al., 2011).

$$A_{1\ or\ 2} = \frac{55.3V}{cRT_{1\ or\ 2}} - 4Vm \qquad \text{(Equation 12)}$$

$\mathrm{V} = \text{Volume of the reverbertation room } (m^3)$

$\mathrm{c} = \text{Propagation speed of sound in air, in metres per second} = 331 + 0.6\mathrm{T}$

$\mathrm{T} = \text{Air Temperature } (°\mathrm{C})$

$\mathrm{RT}_1 = \text{Reverberation time, } \mathrm{RT}_{60}\text{, without the test sample in the room } (s)$

$\mathrm{RT}_2 = \text{Reverberation time, } \mathrm{RT}_{60}\text{, with the test sample in the room (s)}$

$\mathrm{m} = P\text{ower attenuation coefficient, calcluated in ISO 9613} - 1 \text{ for each one third octave band.}$

The sound absorption area of the test specimen in square metres, A_{SAMPLE}, is then calculated using Equation 13.

$$A_{SAMPLE} = A_1 - A_2 \qquad \text{(Equation 13)}$$

This is then used to find the sound absorption coefficient, α_s, using Equation 14. Where s is the area of the fabric in square meters.

$$\alpha_s = \frac{A_{SAMPLE}}{s} \qquad \text{(Equation 14)}$$

5.4.1.1.2 Practical Sound Absorption Coefficient (α_{pi})

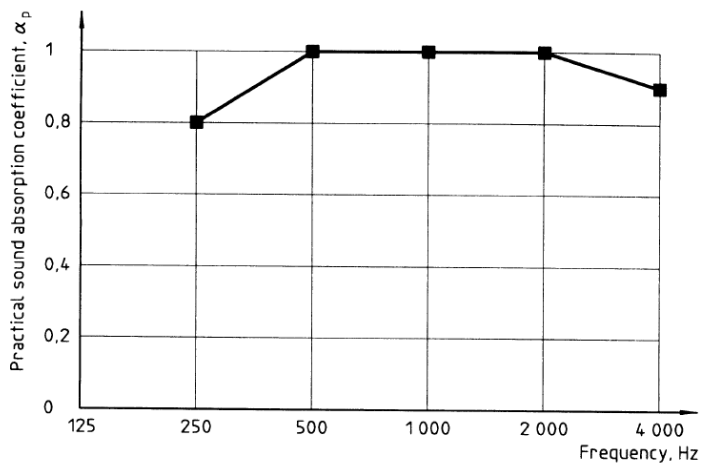
A Practical Sound Absorption Coefficient, α_{pi}, can then be calculated for each octave band between 250 Hz and 4,000 Hz from the sound absorption coefficients (α_s) produced for each one-third octave band using Equation 15 (BSI, 1997).

$$\alpha_{pi} = \frac{\alpha_{s,i1} + \alpha_{s,i2} + \alpha_{s,i3}}{3} \qquad \text{(Equation 15)}$$

The α_s are given ith terms which correspond to each one-third octave band α_s. For example, to derive the α_{pi} for the 250 Hz octave band the α_s values for 200 ($\alpha_{s, i1}$), 250 ($\alpha_{s, i2}$), and 315 ($\alpha_{s, i3}$) Hz are averaged. The mean is calculated to two decimals and rounded in steps of 0.05 to give the Practical Sound Absorption Coefficient, α_{pi}. The α_{pi} cannot exceed 1.

5.4.1.1.3 Weighted Sound Absorption Coefficient, (α_{pi}), ISO Classification and Shape Indicators

Once the α_{pi} for 250 - 4000 Hz octave bands has been calculated the Weighted Sound Absorption Coefficient, α_w, can be derived. This is done by plotting the α_{pi} for each of the octave bands against the reference curve provided in Figure 114 as per BS EN ISO 11654 (BSI, 1997).



Frequency	250 Hz	500 Hz	1 000 Hz	2 000 Hz	4 000 Hz
Value	0,80	1,00	1,00	1,00	0,90

Figure 114. Reference curve for evaluation of Weighted Sound Absorption Coefficient, α_w as per BS EN ISO 11654 (BSI, 1997).

The reference curve is shifted in steps of 0.05 toward the measured α_{pi} curve until the sum of the reference curve deviations is less than or equal to 0.10. The α_w is defined as the value of the shifted reference curve at 500 Hz.

An additional 'Shape Indicator' is provided alongside the α_w when it is reported. This further describes the absorptive properties of a tested sample. It highlights when the α_{pi} value exceeds the reference curve by 0.25 or more, thus identifying when the sample provides more absorption than depicted by the standard reference curve. Depending on the frequency that is exceeded a different notation is provided. An excess of absorption at 250 Hz is noted by an "L" for Low; 500 Hz or 1 kHz uses "M" for Medium; and for 2 or 4 kHz, the notation "H" for High is used.

BS EN ISO 11654 (BSI, 1997) also provides a method for the Weighted Sound Absorption Coefficient, α_w, to be classified into a general grade of effectiveness as per Table 57. This allows for easy comparison between material samples. The classification scale goes from A to E. A Class A absorber is considered best performing because it can absorb the most sound over all octave frequency bands and corresponds to $\alpha_w \geq 0.90$. A product given a Class E classification represents a poor performing absorber with a $0.25 \leq \alpha_w < 0.15$. Products achieving an $\alpha_w \leq 0.10$ are considered 'Not Classified' and are unable (or have very limited ability) to absorb sound (BSI, 1997).

Table 57. Classification of porous sound absorbers as per BS EN ISO 11654 (BSI, 1997)

Class	Wighted Sound Absorption Coeffcient (α_w)
A	1.00, 0.95, 0.90;
B	0.85, 0.80;
C	0.75, 0.70, 0.65, 0.60;
D	0.55, 0.50, 0.45, 0.40, 0.35, 0.30;
E	0.25, 0.20,0.15;
Not Classified	0.10, 0.05, 0.00;

5.4.1.2 Predicting the Reverberation Time (RT) of a Room

In early building design or during retrofit acousticians can predict the reverberation time, RT, of a room and select specific surface finishes to meet a recommended RT using Sabines formulae. A summary of the methodology for how this is carried out is outlined by Peters et al. (2011) and briefly described here.

Sabines formulae is simplified and rearranged (as per Equation 16) to predict the reverberation time, RT (in seconds), of a room which can be done if the volume (V) and the total acoustic absorption area ($\alpha_{A,TOTAL}$) of all the surfaces within a room are known.

$$\mathrm{RT} = 0.16 \frac{\mathrm{V}}{\alpha_{\mathrm{A,TOTAL}}} \qquad \text{(Equation 16)}$$

In early building design this typically considers the walls, ceiling, flooring and any glazing surface. To calculate the acoustic absorption area (α_A) of a material the absorption coefficient (α) of the material is multiplied by the area (A) of the material (as per Equation 17).

$$\alpha_A = \alpha \mathrm{A} \qquad \text{(Equation 17)}$$

The total acoustic absorption area ($\alpha_{A,TOTAL}$) of a room is then calculated by summing the acoustic absorption area (α_A) of each material (as per Equation 18).

$$\alpha_{A,TOTAL} = \alpha_{A1} + \alpha_{A2} + \alpha_{A3} + \cdots \quad \text{(Equation 18)}$$

This method is used by acousticians to identify in the early stages of building design what the likely RT of a room will be. The Department for Education (DfE, 2015), recommends that the mid-frequency reverberation time (RT_{mf}) for new build offices are < 1.0 s and for retrofit is < 1.2 s. The RT_{mf} is the arithmetic average of the reverberation times at 500 Hz, 1000 Hz, and 2000 Hz for rooms that are finished, furnished for normal use, but unoccupied.

Within this study this acoustic assessment method was used to calculate the predicted RT and the RT_{mf} of a room with and without the most absorptive shading fabric to ascertain how the inclusion of a shading product would alter the RT of a specific room. For the purposes of this study, the dimensions and material construction of the case study office evaluated in Chapter 4 (Health, Well-being, Comfort and Productivity) was used as the base case.

5.4.1.3 Reverberation Room

Testing was conducted within a reverberation room. The reverberation room used was located at London South Bank University and complied with the requirements of BS EN ISO 354:2003. The room was < 200 m^3 measured at 203 m^3 and was constructed and furnished with non-porous highly reverberant materials. Figure 115 shows the empty reverberation room.

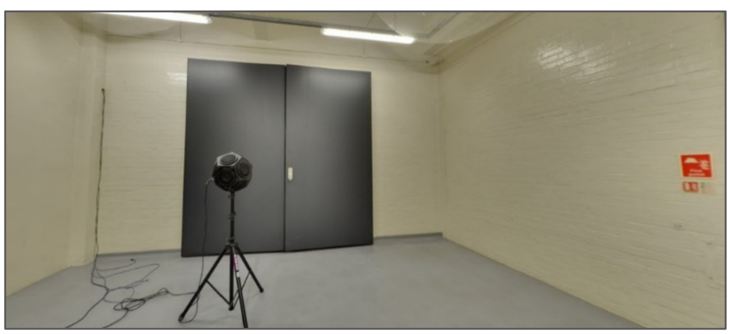


Figure 115. Reverberation room

5.4.1.4 Equipment Setup

Six measurements were taken from two microphones resulting in twelve measurements which were then used to calculate the average RT[47]. For each measurement, the position of either the microphone or the sound source differed. The position of the two omni-directional microphones varied between 1 of 3 positions and the sound source varied

[47] Twelve measurements are the minimum number of measurements required by BS EN ISO 354 (BSI, 2003)

between 1 of 2 positions. Figure 116 illustrates the positions of the equipment for each of the six recordings. Minimum distances for the microphones and sound source from one another and the surrounding walls and the test sample are prescribed in BS EN ISO 354 (BSI, 2003).

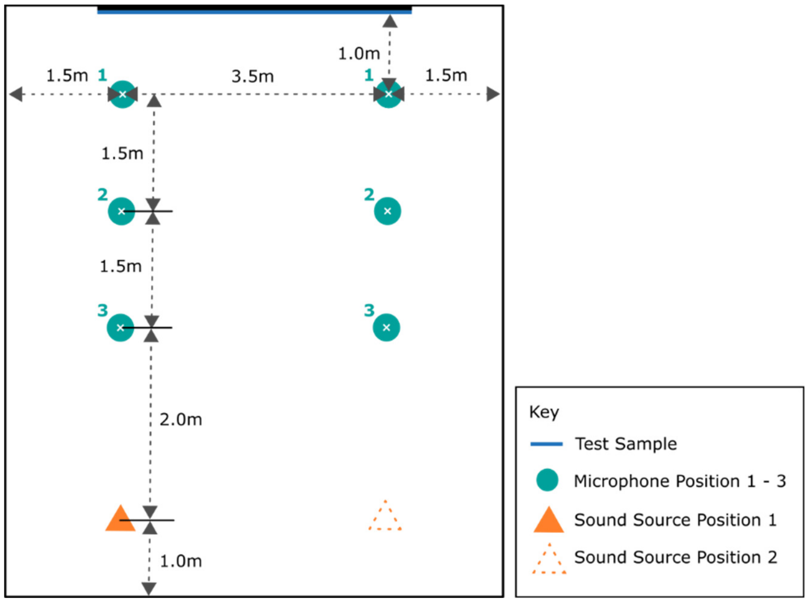


Figure 116. Layout of the equipment within the reverberation room

For the first two measurements the microphones and the sound source were placed in position one. For the third and fourth measurement the microphones were moved to position two and the sound source remained in position one. For the fifth and sixth measurement the microphones were moved to position three and the sound source remained in the same position. These steps were then repeated with the sound source in position two for measurements seven to twelve.

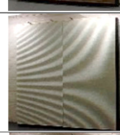
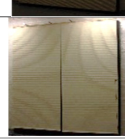
Figure 117. Loudspeaker (Top Left), Microphone (Top Right) and Norsonic Nor121 Environmental Analyser (Bottom)

Two omnidirectional microphones and microphone stands, one Brüel & Kjær Precision Type 4224 Sound Source amplified loudspeaker and one Norsonic Nor 121 Environmental Analyser were used as pictured in Figure 117. The Nor 121 Sound Analyser was located outside the reverberation room but was directly connected to the sound source and the microphones. An access tube in the reverberation room wall provided a connection to the equipment without impacting the acoustic conditions of the room.

5.4.1.5 Shading Test Samples

For consistency between the two studies the same fabrics used in the transmission testing were used in the absorption testing. These varied in material composition, material thickness and structure/form. Fabric data of each of the samples is presented in Table 58.

Table 58. Material properties of samples for absorption testing.

Sample	Image	Material	Thickness (+/- 5%)	Weight (+/- 5%)	Sample Area	Fabric Structure
A		42% Fibreglass / 58% PVC	0.75 mm	520 g/m^2	10.37m^2	Flat
B		Coated Fibreglass Fabric	0.55 mm	430 g/m^2	10.37 m^2	Flat
C		36% Fibreglass / 64% PVC	0.42 mm	340 g/m^2	10.37 m^2	Flat
D		36% Fibreglass / 64% PVC	0.52 mm	380 g/m^2	10.10 m^2	Flat
E		100% Polyester	0.42 mm	260 g/m^2	10.37 m^2	Flat
F		100% Polyester	0.25 mm	320 g/m^2	10.93 m^2	Honeycomb
G		100% Polyester	0.42 mm	495 g/m^2	10.34 m^2	Honeycomb
H		100% Polyester	0.25 mm	290 g/m^2	10.00 m^2	Honeycomb

5.4.1.6 Mounting Samples

The standard specifies that a sample ≥ 10 m^2 is tested within the reverberation room. Each shading device supplied measured approximately 3.20 m wide x 3.20 m drop and was tested with the bottom bar supplied by the manufacturer to ensure the shading device was under tension equivalent to a real-world installation. Where a bottom bar was not provided a weight was inserted into a fold at the bottom of the fabric (See Figure 118).

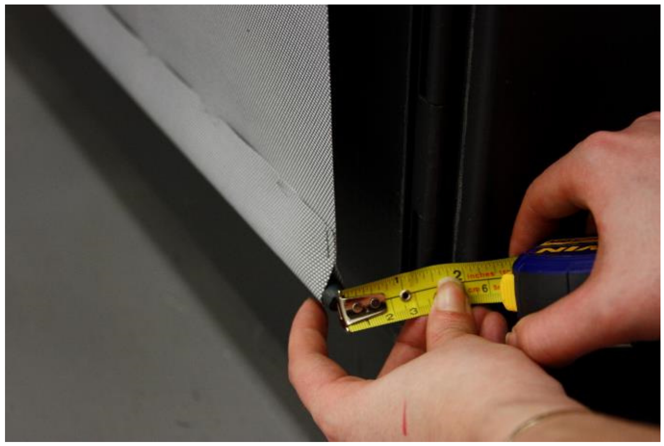


Figure 118. Measuring shading fabric distance

Within BS EN ISO 354: 2003 the guidance for a Type G Mounting was followed. The samples were hung parallel to a surface within the room. The standard specifies that the distance between the front face of the test specimen and the room surface should be tested at 100 mm and if additional distances are required these should be of integral multiples of 50 mm. Internal shading products are more commonly mounted at smaller distances from a window therefore the researcher chose to position and additionally test the shading fabrics at 15, 30 and 300 mm. 15 mm reflects the position of an internal shading product installed as part of a zipped system (which is fixed to the window frame), 30 mm reflects an internal shading product installed inside the window reveal, 100 mm is relevant to the installation of an internal shading product installed outside the window reveal and the 300 mm distance reflects a shading product installed as a sail which is another type of internal shading product more conventionally used to improve acoustic absorption in heavily glazed buildings. In total four distances (15, 30, 100 and 300 mm) were measured, tested, and analysed to identify the impact the distance of the shading fabric has on the absorption acoustic properties of the shading product.

An adjustable rig was manufactured and fixed on top of the metal cabinet within the room. The rig was constructed of four slotted metal bars and four wooden supports. Each shading fabric was fixed (with staples and adhesive) to a wooden batten that could be connected to the three slotted metal bars. The batten (attached to the shading fabric) could slide to and from the front face of the metal cabinet. Figure 119 shows the rig and mounting setup.

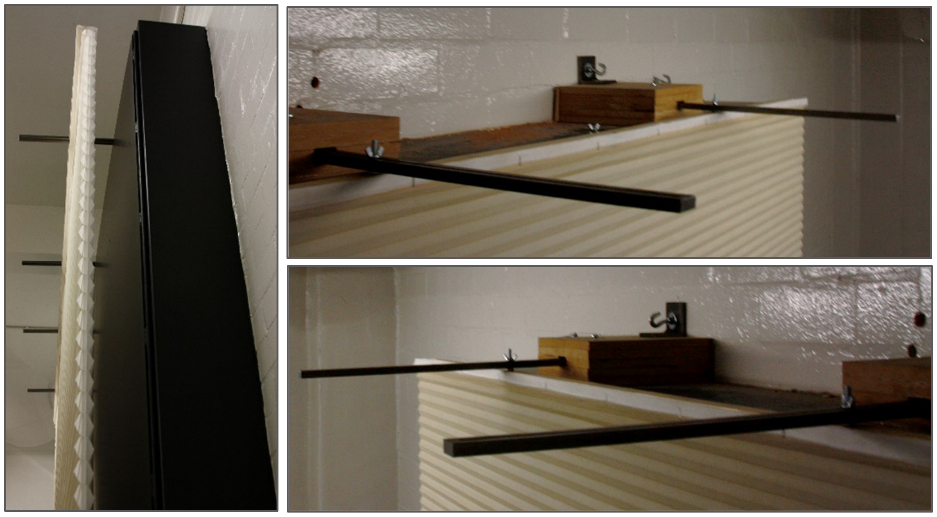


Figure 119. Mounting rig

The distance between the front face of the shading fabric and the vertical room surface of the metal cabinet was measured at the bottom, middle and top of the fabric before testing began (see Figure 118 and Figure 120). Whilst there were some deviations due to the way the material hung best efforts were made to keep the distance uniform.

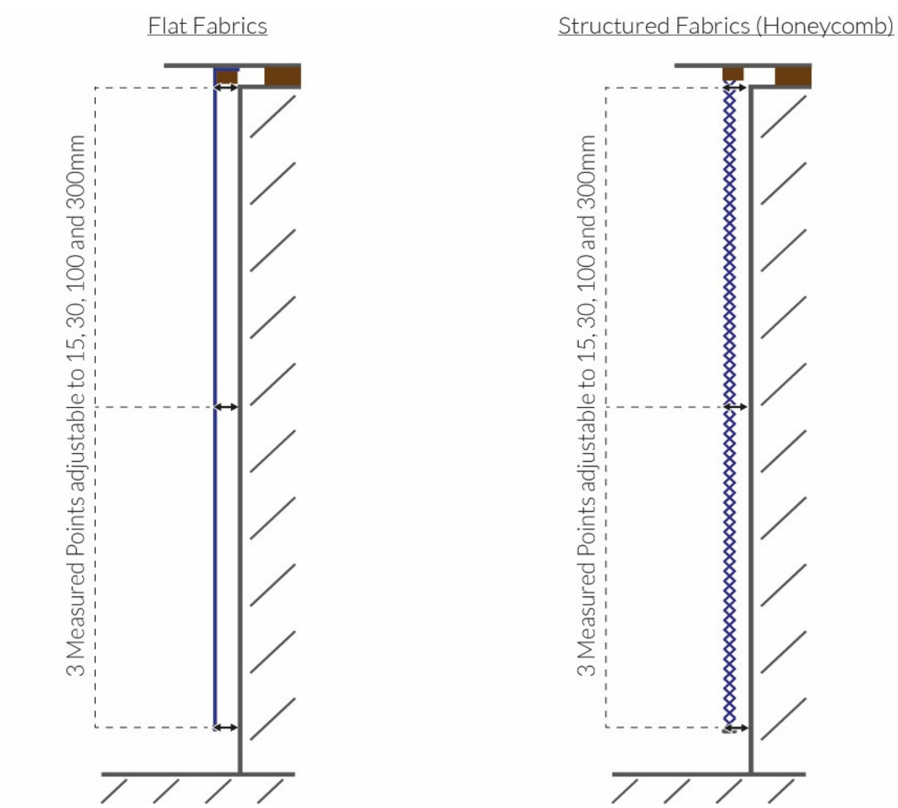


Figure 120. Mounting of shading fabrics within the reverberation room

5.4.1.7 Data Collection Procedure

Each fabric sample was installed in the reverberation room and individually tested. The room was also tested without the sample in the room to provide a control RT for the room. The following procedure was carried out to measure the sound decay of the room with and without the fabric samples:

1. The air temperature and relative humidity within the reverberation room were recorded before each set of measurements were collected[48].
2. The room was then vacated and sealed.
3. Broadband noise generated by the Nor 121 Sound Analyser was emitted by the loudspeaker filling the reverberation room until the Sound Power Level (SPL) reached a stationary average. The SPL was measured by the two omnidirectional microphones.
4. Once a stationary average SPL was met the source sound stopped, a 5 dB drop across all one third octave frequencies was measured[49] (as specified in BS EN ISO 354) and then the time taken for the SPL to decay by a further 20 dB, RT_{20}, and 30 dB, RT_{30}, was measured[50].
5. The room was then entered and the microphones (and loudspeaker if needed) were repositioned. Steps 2 - 5 were then repeated until data for each test position had been collected.

The Nor 121 Sound Analyser automatically carries out Steps 3 and 4 removing human error from the testing procedure. This process provided 12 measurements recorded by the two microphones. The resulting 12 independent decay curves were then averaged to achieve a smoother and more reliable decay curve providing one set of normalised RT_{60} results for each test sample and the empty control room. The difference between the time taken for the sound to decay is attributed to the absorptive properties of the test sample. However, if during the testing the measurements were interfered with (identified by observing the live reporting of the sound decay on the Nor 121 analyser) they were immediately discarded and retested before the decay curve was averaged. This process was then

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[48] The room was kept within the testing requirements, relative humidity was between 30 and 90% and the air temperature did not go below 15 °C during the tests.
[49] BS EN ISO 354 (BSI, 2003) requires one third octave bands with the following centre frequency to be measured: 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1000, 1250, 1600, 2000, 2500, 4000, 5000 Hz.
[50] The RT_{20} measurement provides a shorter linear extrapolation of the typically described reverberation time, RT_{60}. It is rare that a full 60-dB decay can be measured due to ambient background noise or spikes in reverberation. The Nor 121 Analyser outputs a pre-normalised RT_{20} and RT_{30} measurement that is equivalent to the RT6o measurement required to calculate the α_s.

repeated for each of the test samples positioned at differing distances from the back panel (at 15, 30, 100 and 300 mm).

5.4.2 Analysis and Results

5.4.2.1 Sound Absorption Coefficient, α_s, Practical and Weighted Sound Absorption Coefficient and ISO Classification.

The reverberation time of the room without a fabric sample was measured multiple times across the testing sessions to account for variation in environmental conditions. Environmental measurements ranged between 18 - 20°C and between 52 - 55% RH, within the constraints defined by BS EN ISO 354:2003 (BSI, 2003). During these measurements, the empty room also included the rig and batten used to mount the fabric sample as the objective was to evaluate the absorptive properties of the shading fabric alone.

When the sample was included within the room the environmental measurements ranged between 18 - 20°C and 45 - 57% RH which were well within the constraints defined in BS EN ISO 354 (BSI, 2003). The RT_{60} data collected across one-third octave bands were used within Equation 12 - 14 to produce the Sound Absorption Coefficient (αs) and these results are presented in 0. 0 also presents the Practical Sound Absorption (α_{pi}) for each octave band and the overall Weighted Sound Absorption (α_s) with its corresponding ISO Class and Shape Indicator reference for each sample at the differing distances tested. The following sections describe these results in further detail.

Table 59. Sound Absorption Coefficient (α_s) measurement data for one-third octaves between 100 Hz – 5KHz, Practical Sound Absorption (α_p) measurement data for octave bands, Weighted Sound Absorption (α_w), Shape Indicator (H = High, M = Medium, L = Low) and ISO Class for all samples at differing mounting

		Sound Absorption Coefficient (α_s) in one-third octave bands																		Practical Sound Absorption (α_{pi}) in octave bands					Weighted Sound Absorption (α_w)	Shape Indicator	ISO Class
Sample	Mounting Distance (mm)	Frequency (Hz)																		Frequency (Hz)							
		100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	250	500	1000	2000	4000			
A	15	0.02	0.01	-0.05	0.05	0.00	-0.06	0.01	0.00	0.01	0.01	0.01	0.04	0.06	0.07	0.08	0.11	0.16	0.22	0.00	0.00	0.00	0.05	0.15	0.00	-	No Class
	30	0.00	0.02	-0.07	0.00	0.03	-0.01	0.02	0.02	0.03	0.03	0.05	0.08	0.14	0.19	0.22	0.23	0.25	0.23	0.00	0.00	0.05	0.20	0.25	0.05	H	No Class
	100	0.06	0.02	-0.03	0.05	0.04	0.01	0.06	0.07	0.12	0.13	0.17	0.18	0.13	0.09	0.14	0.16	0.18	0.23	0.05	0.10	0.15	0.10	0.20	0.15	-	E
	300	0.06	0.08	0.01	0.11	0.13	0.12	0.14	0.07	0.07	0.08	0.14	0.12	0.13	0.13	0.17	0.17	0.20	0.25	0.10	0.10	0.10	0.15	0.20	0.15	-	E
B	15	-0.03	-0.01	-0.05	0.00	0.01	-0.02	0.04	0.02	0.05	0.08	0.11	0.15	0.24	0.33	0.42	0.53	0.59	0.74	0.00	0.05	0.10	0.35	0.60	0.00	-	No Class
	30	0.00	0.06	-0.06	0.04	0.02	0.01	0.04	0.10	0.15	0.17	0.25	0.38	0.52	0.56	0.67	0.71	0.77	0.74	0.00	0.10	0.25	0.60	0.75	0.20	H	E
	100	-0.02	0.02	-0.01	0.17	0.17	0.25	0.33	0.49	0.51	0.67	0.68	0.67	0.59	0.47	0.58	0.60	0.61	0.65	0.20	0.45	0.65	0.55	0.60	0.45	H	D
	300	0.09	0.13	0.20	0.38	0.52	0.53	0.61	0.53	0.41	0.45	0.56	0.51	0.57	0.56	0.59	0.57	0.65	0.65	0.50	0.50	0.50	0.55	0.60	0.55	-	D
C	15	0.00	0.01	-0.11	0.04	-0.03	-0.08	-0.01	0.00	0.02	0.03	0.03	0.03	0.05	0.05	0.07	0.07	0.13	0.19	0.00	0.00	0.05	0.05	0.15	0.00	-	No Class
	30	0.04	0.00	-0.06	0.02	0.02	-0.03	0.02	-0.01	0.01	0.02	0.03	0.02	0.06	0.09	0.12	0.12	0.18	0.19	0.00	0.00	0.05	0.10	0.15	0.05	-	No Class
	100	-0.03	0.02	-0.09	0.00	0.00	-0.05	0.02	0.03	0.06	0.07	0.10	0.09	0.07	0.05	0.08	0.11	0.15	0.18	0.00	0.05	0.10	0.05	0.15	0.00	-	No Class
	300	-0.04	-0.04	-0.06	0.03	0.07	0.01	0.05	0.05	0.03	0.02	0.03	0.05	0.06	0.07	0.08	0.11	0.16	0.20	0.05	0.05	0.05	0.05	0.15	0.05	-	No Class
D	15	0.01	0.00	-0.04	0.00	0.01	-0.04	0.03	0.01	0.01	0.02	0.02	0.04	0.05	0.08	0.12	0.15	0.18	0.22	0.00	0.00	0.05	0.10	0.20	0.00	-	No Class
	30	0.00	0.00	-0.11	0.02	0.01	-0.01	0.00	0.03	0.03	0.04	0.07	0.08	0.14	0.16	0.18	0.20	0.21	0.18	0.00	0.00	0.05	0.15	0.20	0.05	-	No Class
	100	0.07	0.04	-0.05	0.03	0.00	-0.04	0.03	0.05	0.10	0.15	0.15	0.15	0.10	0.09	0.13	0.14	0.15	0.22	0.00	0.05	0.15	0.10	0.15	0.00	-	No Class
	300	0.02	0.05	0.01	0.09	0.06	0.06	0.13	0.09	0.05	0.06	0.09	0.07	0.11	0.11	0.13	0.15	0.17	0.19	0.05	0.10	0.05	0.10	0.15	0.10	-	No Class
E	15	-0.01	0.04	-0.09	-0.01	-0.04	-0.02	0.03	0.05	0.11	0.19	0.32	0.47	0.51	0.52	0.52	0.50	0.52	0.49	0.00	0.05	0.35	0.50	0.50	0.15	H	E
	30	0.01	-0.02	-0.08	0.05	0.03	0.00	0.05	0.11	0.22	0.43	0.49	0.58	0.57	0.53	0.54	0.50	0.51	0.52	0.05	0.15	0.50	0.55	0.50	0.25	M/H	E
	100	0.01	0.00	-0.08	0.03	0.03	0.06	0.21	0.31	0.37	0.43	0.42	0.39	0.37	0.39	0.47	0.45	0.49	0.56	0.05	0.30	0.40	0.40	0.50	0.30	H	D
	300	0.07	0.02	0.00	0.05	0.05	0.11	0.16	0.18	0.20	0.31	0.34	0.36	0.44	0.43	0.52	0.52	0.57	0.60	0.05	0.20	0.35	0.45	0.55	0.25	H	E
F	15	0.05	0.04	0.05	0.02	0.06	0.09	0.10	0.12	0.16	0.17	0.22	0.33	0.43	0.54	0.60	0.68	0.76	0.78	0.05	0.15	0.25	0.50	0.75	0.25	H	E
	30	0.06	0.01	0.01	0.02	0.06	0.09	0.09	0.14	0.23	0.29	0.37	0.52	0.63	0.68	0.78	0.79	0.76	0.75	0.05	0.15	0.40	0.70	0.75	0.25	H	E
	100	0.07	0.04	0.06	0.05	0.14	0.23	0.31	0.38	0.51	0.56	0.65	0.67	0.57	0.53	0.65	0.71	0.72	0.75	0.15	0.40	0.65	0.60	0.75	0.40	M/H	D
G	15	0.08	0.09	0.02	0.05	0.09	0.20	0.20	0.25	0.27	0.35	0.47	0.66	0.72	0.83	0.88	0.89	0.88	0.87	0.10	0.25	0.50	0.80	0.90	0.30	H	D
	30	0.10	0.10	0.08	0.11	0.13	0.20	0.27	0.34	0.42	0.52	0.67	0.84	0.86	0.89	0.85	0.82	0.80	0.78	0.15	0.35	0.70	0.85	0.80	0.40	M/H	D
	100	0.16	0.05	0.14	0.18	0.15	0.34	0.44	0.54	0.60	0.74	0.83	0.76	0.65	0.68	0.74	0.81	0.87	0.81	0.20	0.55	0.75	0.70	0.85	0.50	M/H	D
H	15	0.08	0.11	0.03	0.10	0.07	0.17	0.18	0.22	0.29	0.37	0.48	0.56	0.66	0.81	0.89	0.91	0.95	0.93	0.10	0.25	0.45	0.80	0.95	0.30	H	D
	30	0.06	0.07	0.05	0.13	0.10	0.12	0.22	0.30	0.37	0.45	0.60	0.73	0.84	0.92	0.94	0.95	0.89	0.88	0.10	0.30	0.60	0.90	0.90	0.35	M/H	D
	100	0.09	0.10	0.06	0.14	0.27	0.39	0.53	0.62	0.66	0.78	0.88	0.83	0.70	0.69	0.84	0.83	0.89	0.91	0.25	0.60	0.85	0.75	0.90	0.55	M/H	D

distances.

5.4.2.2 Practical Sound Absorption Coefficient (α_{pi})

The α_{pi} data presented in 0 are also presented in Figure 121 - Figure 128. Each graph displays a single samples results with the α_{pi} plotted for each octave band and for each of the differing mounting distances. Additionally, coloured reference curves have been plotted on each graph that reflect the ISO classification of the samples according to BS EN ISO 11654 (BSI, 1997).

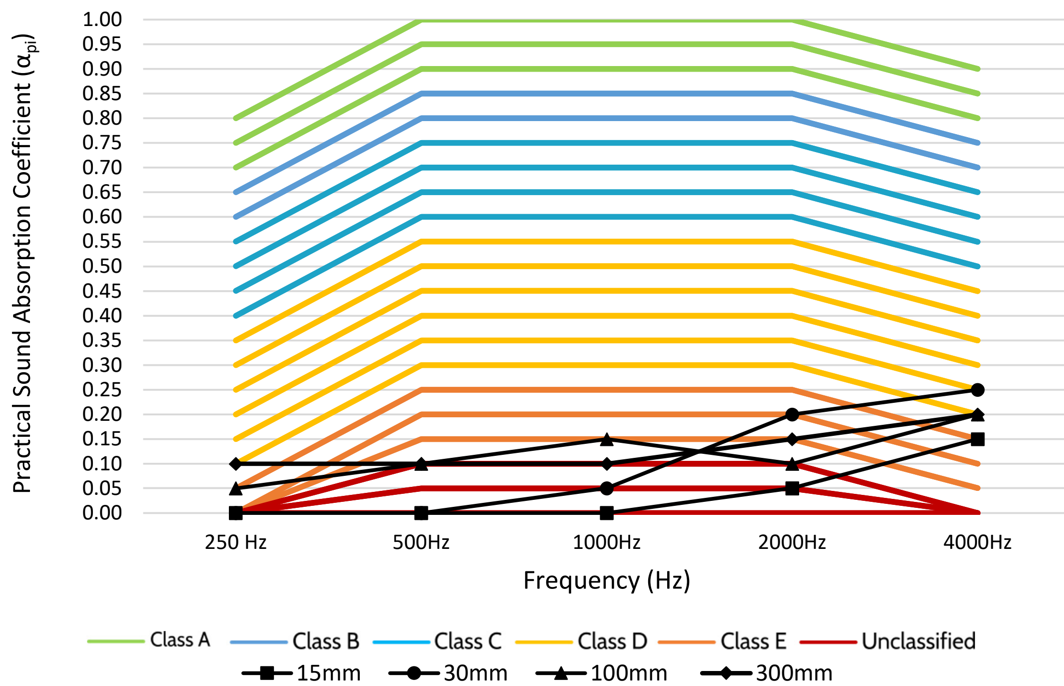

Figure 121. Practical Sound Absorption Coefficient (α_{pi}) for Sample A at 15, 30, 100 and 300 mm mounting distances.

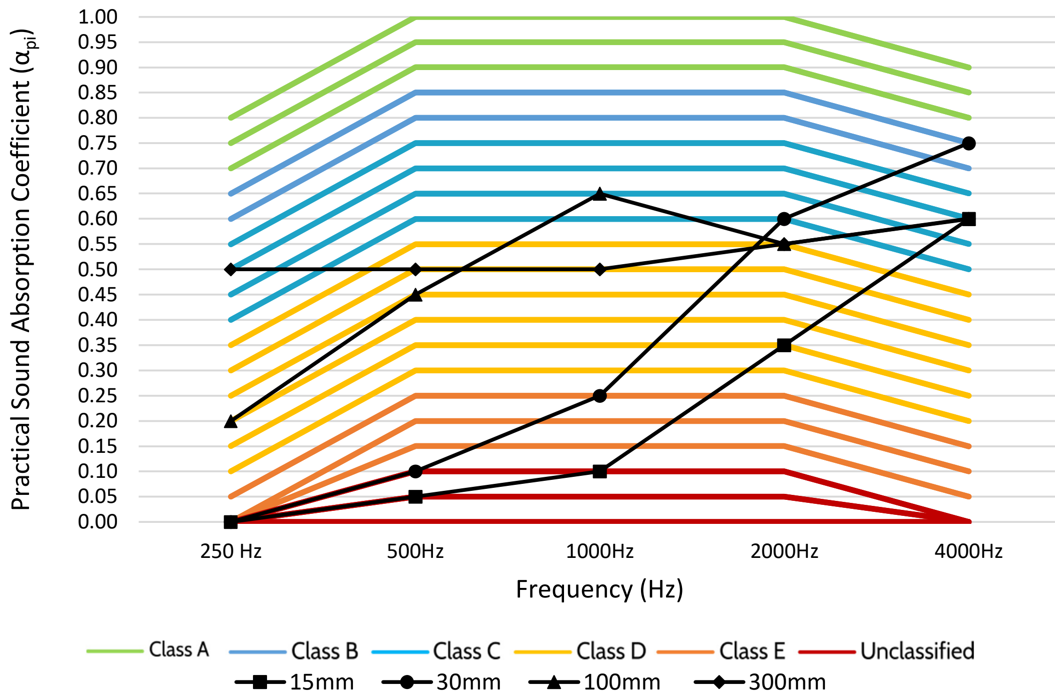

Figure 122. Practical Sound Absorption Coefficient (α_{pi}) for Sample B at 15, 30, 100 and 300 mm mounting distances.

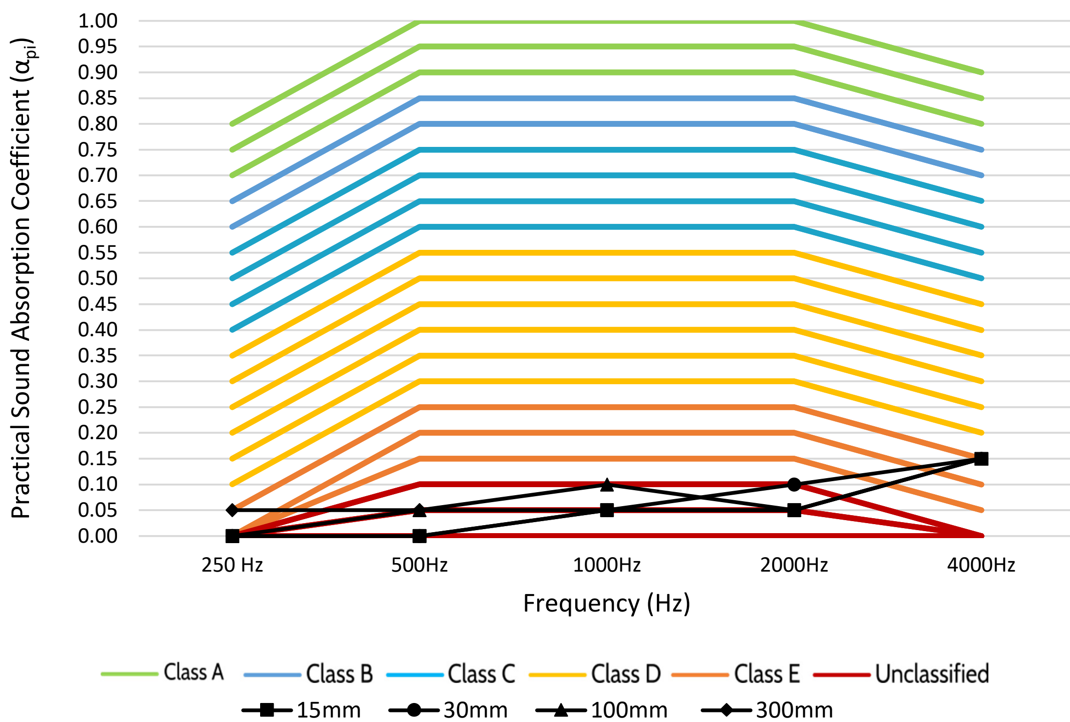

Figure 123. Practical Sound Absorption Coefficient (α_{pi}) for Sample C at 15, 30, 100 and 300 mm mounting distances.

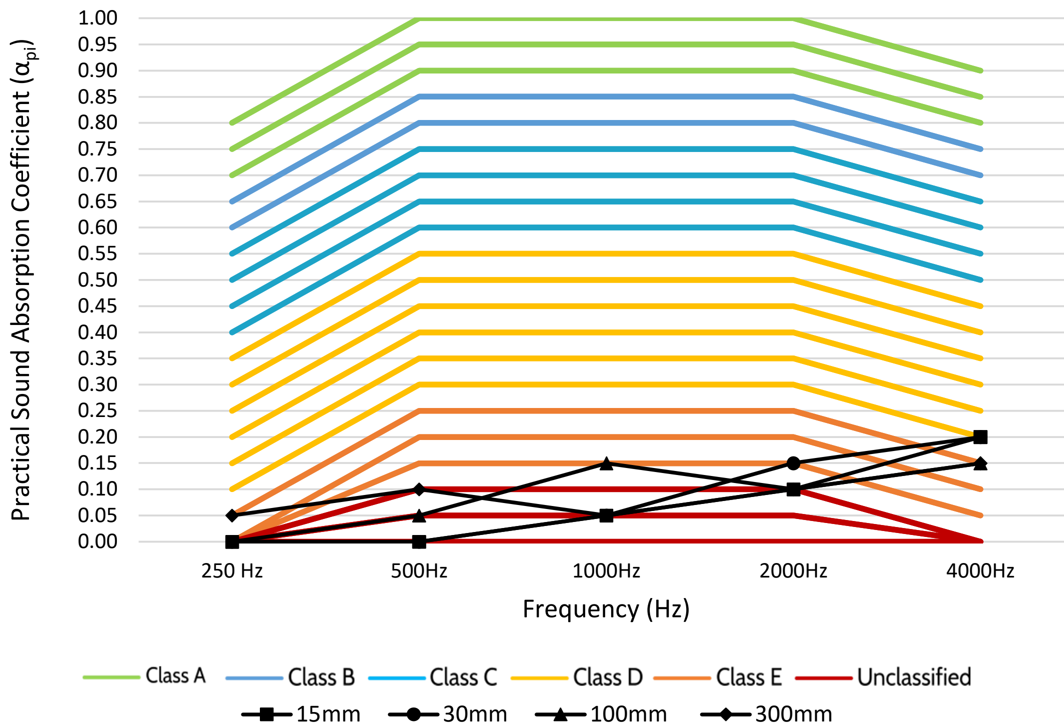

Figure 124. Practical Sound Absorption Coefficient (α_{pi}) for Sample D at 15, 30, 100 and 300 mm mounting distances.

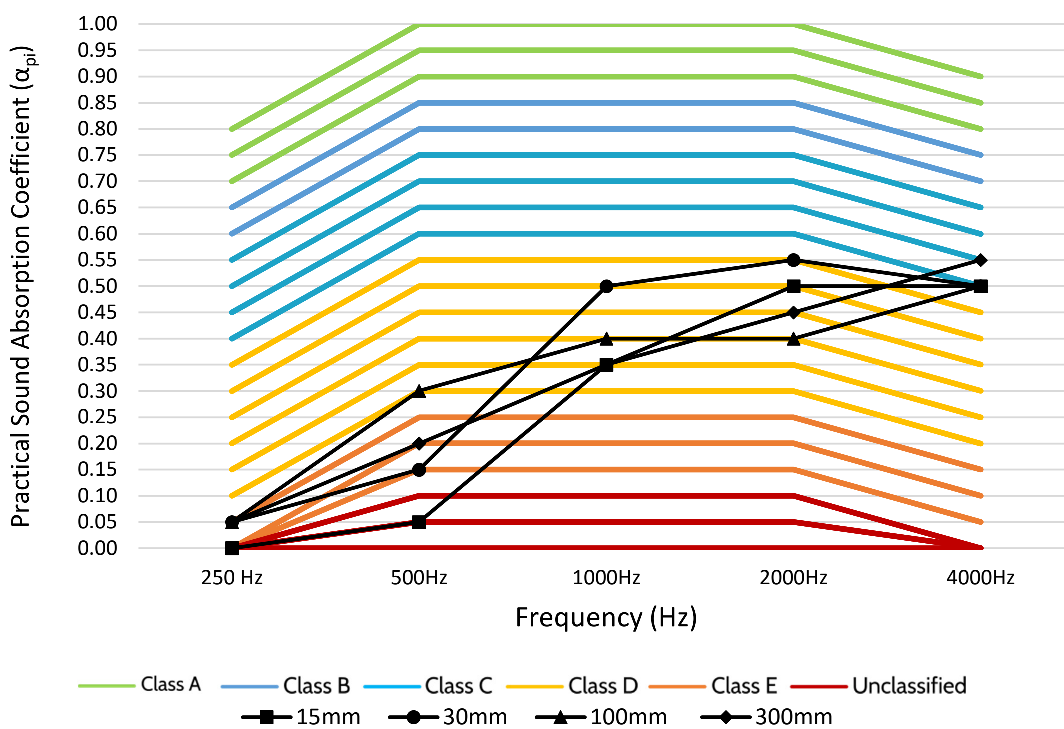

Figure 125. Practical Sound Absorption Coefficient (α_{pi}) for Sample E at 15, 30, 100 and 300 mm mounting distances.

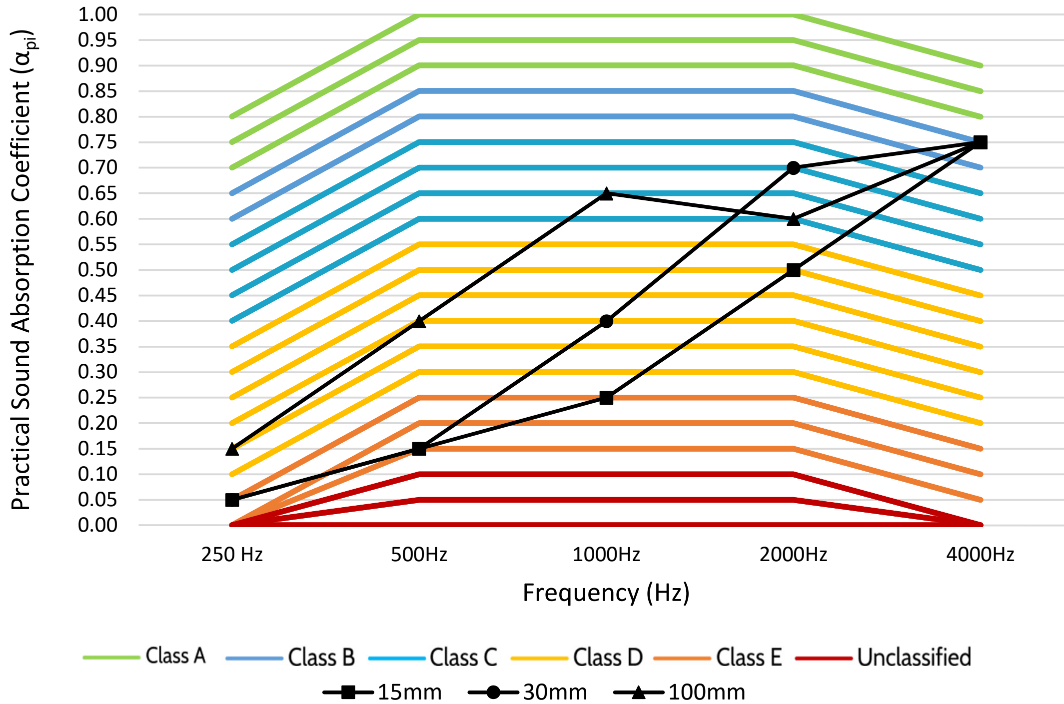

Figure 126. Practical Sound Absorption Coefficient (α_{pi}) for Sample F at 15, 30 and 100 mm mounting distances.

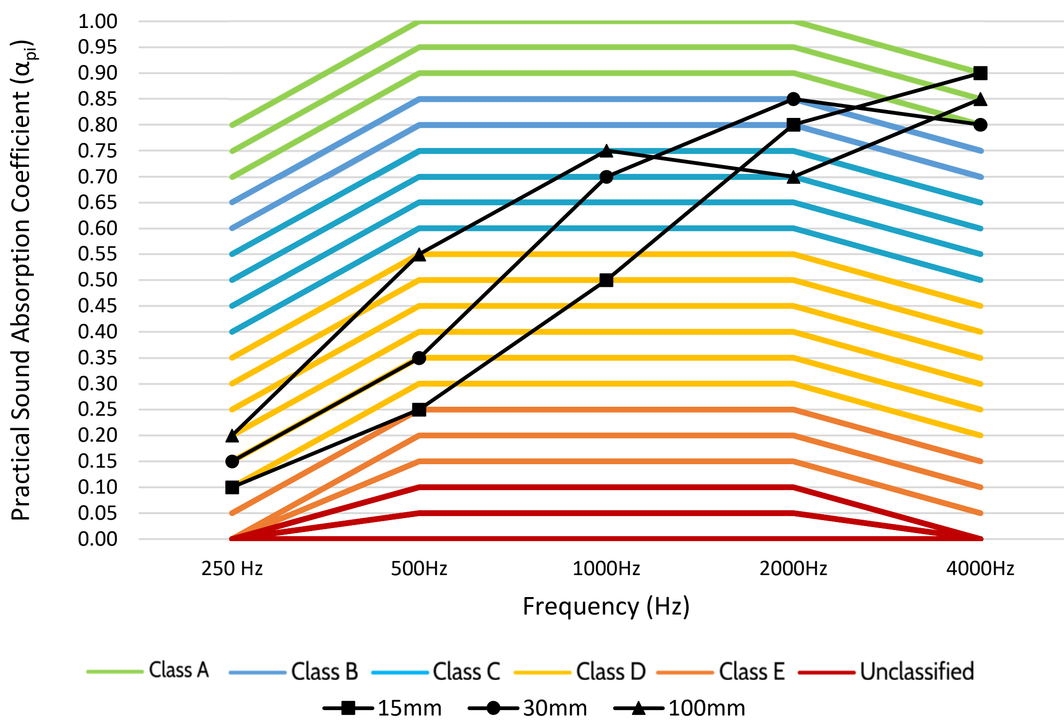

Figure 127. Practical Sound Absorption Coefficient (α_{pi}) for Sample G at 15, 30 and 100 mm mounting distances.

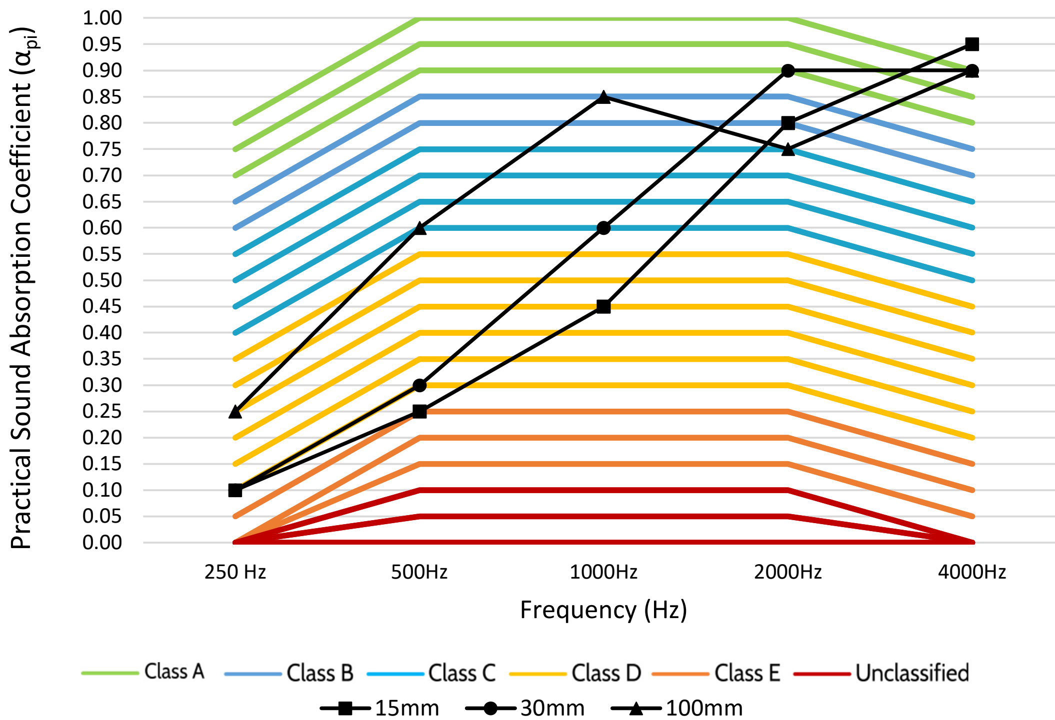

Figure 128. Practical Sound Absorption Coefficient (α_{pi}) for Sample H at 15, 30 and 100 mm mounting distances.

Within Figure 121 - Figure 128 the mounting distance influences the resulting α_{pi} depending on the octave band being assessed. In some cases, the effect is non-linear across the octave bands and results in a bi-modal α_{pi} performance across the octave bands. For example, in Figure 128 (which presents the results for Sample H) when the sample is positioned at a mounting distance of 100 mm as the frequency increases between 250 Hz - 1000 Hz the α_{pi} increases but then reduces at 2000 Hz and then increases again at 4000 Hz. In other cases, the performance is relatively linear across the frequency bands. For example, in Figure 128 when the fabric is mounted at 15 and 30 mm the fabric consistently improves in α_{pi} performance across the octave bands.

To compare the performance of the fabrics between the differing mounting distances more robustly Figure 129 - Figure 133 present the α_{pi} as a bar chart for each octave band (250 Hz, 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz). These data are the same data presented in Figure 121 - Figure 128 and 0. In Figure 129 - Figure 133 where the α_{pi} is zero this means that the sample did not reduce sound at the specific octave band and distance installed. For example, in Figure 129 Sample A did not reduce sound at 250 Hz when installed 15 and 30 mm from the room surface. The coloured dashed lines in each graph represent the lower limit threshold for each ISO Classification as per BS EN ISO 11654 (BSI, 1997).

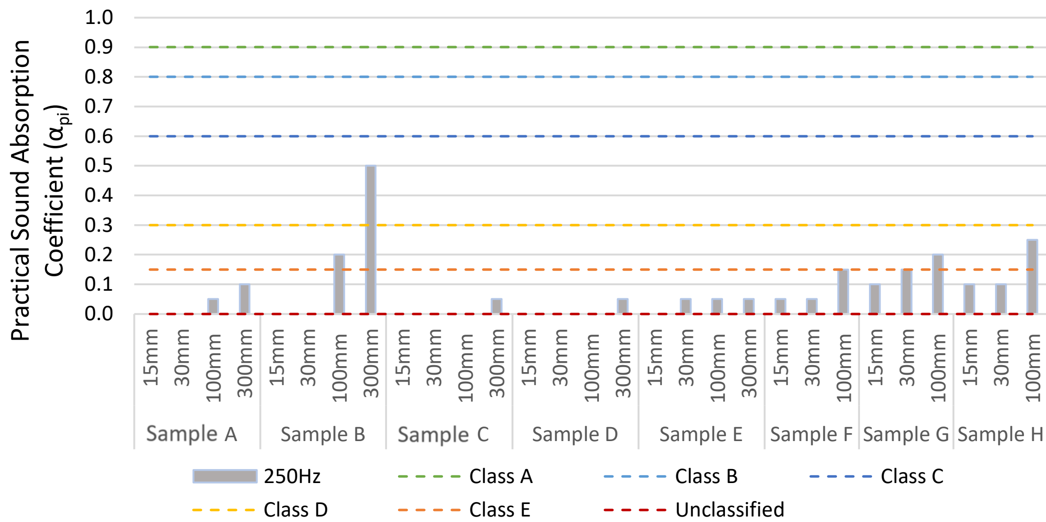

Figure 129. Practical Sound Absorption Coefficient (α_{pi}) for all samples tested at all mounting distances at 250 Hz.

Figure 129 identifies that four of the eight samples effectively absorbed sound and achieved a $\alpha_{pi} \geq 0.15$, equivalent to a Class E or better rating at 250 Hz. Sample B performed best achieving a α_{pi} of 0.50, equivalent to a Class D when mounted at 300 mm. Increasing the mounting distance improved the α_{pi} (or it stayed the same) for all samples tested at 250 Hz.

The way the mounting distance affected the α_{pi} at 250 Hz can be summarised as:

- Between 15 and 30 mm, two of the eight samples α_{pi} increased. The remaining samples α_{pi} stayed the same between the distances.
- Between 30 and 100 mm, five of the eight samples α_{pi} increased. The remaining samples α_{pi} stayed the same between the distances.
- Between 100 and 300 mm, four of the five samples α_{pi} increased. The remaining samples α_{pi} stayed the same between the distances.

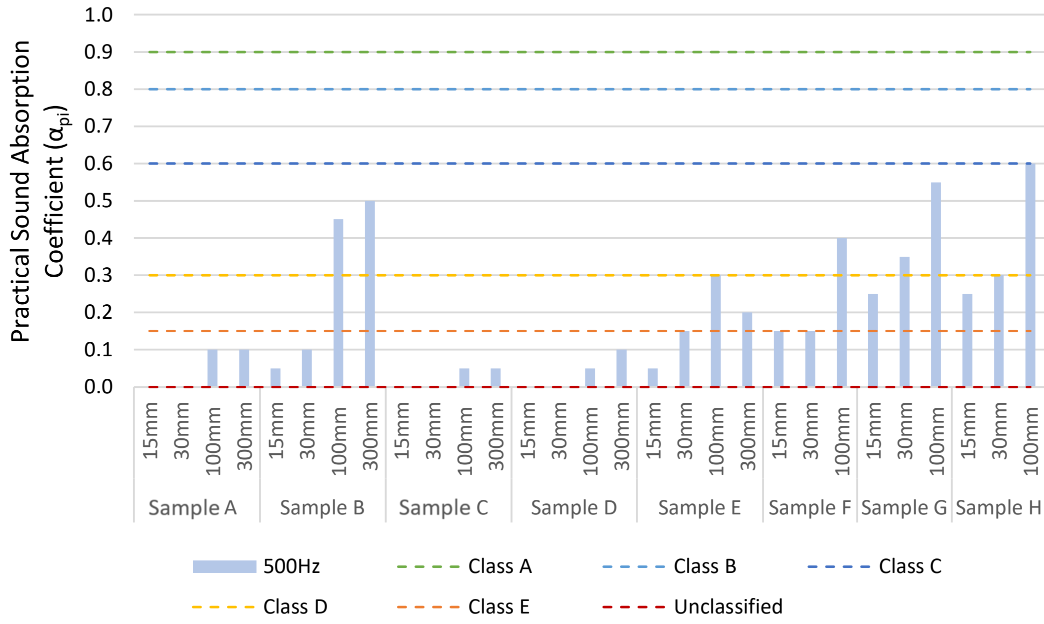

Figure 130. Practical Sound Absorption Coefficient (α_{pi}) for all samples tested at all mounting distances at 500 Hz.

Figure 130 identifies that five of the eight samples effectively absorbed sound and achieved a $\alpha_{pi} > 0.15$, equivalent to a Class E or better rating at 500 Hz. Sample H performed best achieving a α_{pi} of 0.60, equivalent to a Class C when mounted at 100 mm. Increasing the mounting distance improved the α_{pi} for the majority (7 of the 8) of the samples tested at 500 Hz.

The way the mounting distance affected the α_{pi} at 500 Hz can be summarised as:

- Between 15 and 30 mm, four of the eight samples α_{pi} increased. The remaining samples α_{pi} stayed the same between the distances.
- Between 30 and 100 mm, all eight samples α_{pi} increased.
- Between 100 and 300 mm, two of the five samples α_{pi} increased. Two of the five samples α_{pi} stayed the same and one sample (Sample E) α_{pi} decreased.

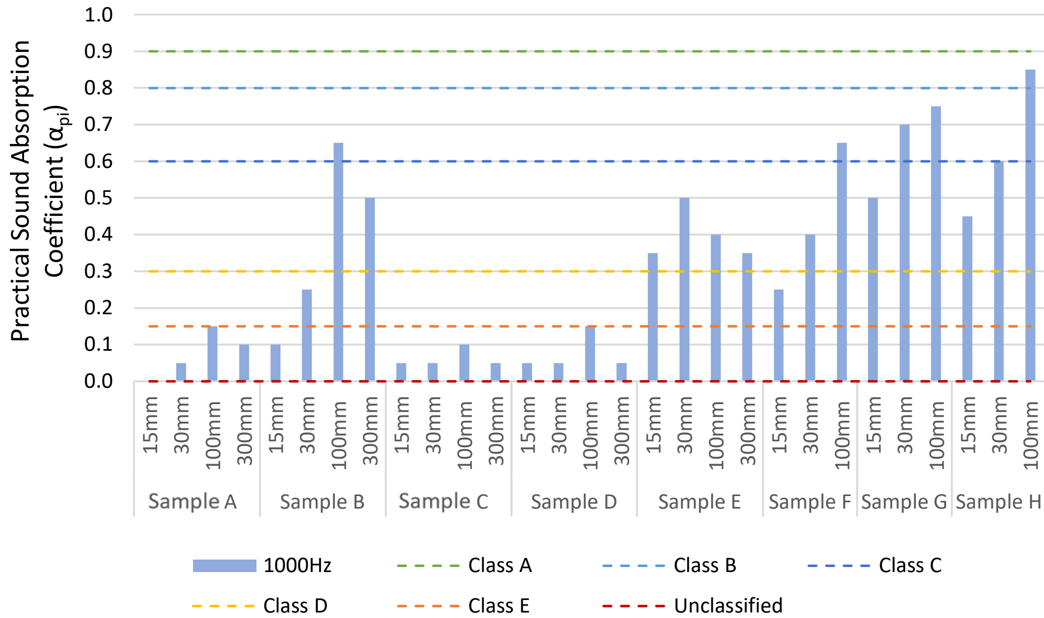

Figure 131. Practical Sound Absorption Coefficient (α_{pi}) for all samples tested at all mounting distances at 1000 Hz.

Figure 131 identifies that seven of the eight samples effectively absorbed sound and achieved a $\alpha_{pi} \geq 0.15$, equivalent to a Class E or above rating at 1000 Hz. Sample H also performed best achieving a α_{pi} of 0.85, equivalent to a Class B when mounted at 100 mm. Increasing the mounting distance improved the α_{pi} for only 3 of the 8 samples consistently at 1000 Hz.

The way the mounting distance affected the α_{pi} at 1000 Hz can be summarised as:

- Between 15 and 30 mm, six of the eight samples α_{pi} increased. The two remaining samples α_{pi} stayed the same between the distances.
- Between 30 and 100 mm, seven of the eight samples α_{pi} increased. The remaining sample (Sample E) α_{pi} decreased between the distances.
- Between 100 and 300 mm, all five samples α_{pi} decreased.

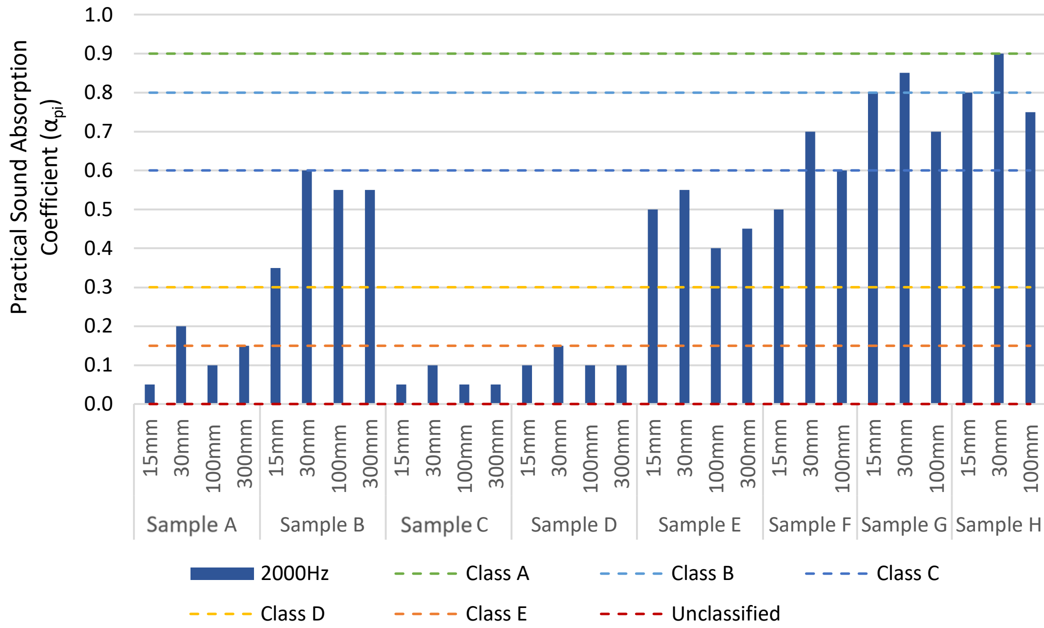

Figure 132. Practical Sound Absorption Coefficient (α_{pi}) for all samples tested at all mounting distances at 2000 Hz.

Figure 132 identifies that six of the eight samples effectively absorbed sound and achieved a $\alpha_{pi} \geq 0.15$, equivalent to a Class E or above rating at 2000 Hz. Sample H performed best achieving a α_{pi} of 0.90, equivalent to a Class A when mounted at 100 mm. Increasing the mounting distance did not consistently improve the α_{pi} for any of the samples at 2000 Hz.

The way the mounting distance affected the α_{pi} at 2000 Hz can be summarised as:

- Between 15 and 30 mm, all eight samples α_{pi} increased.
- Between 30 and 100 mm, all eight samples α_{pi} decreased.
- Between 100 and 300 mm, two of the five samples α_{pi} decreased. The remaining three samples α_{pi} did not change between the two distances.

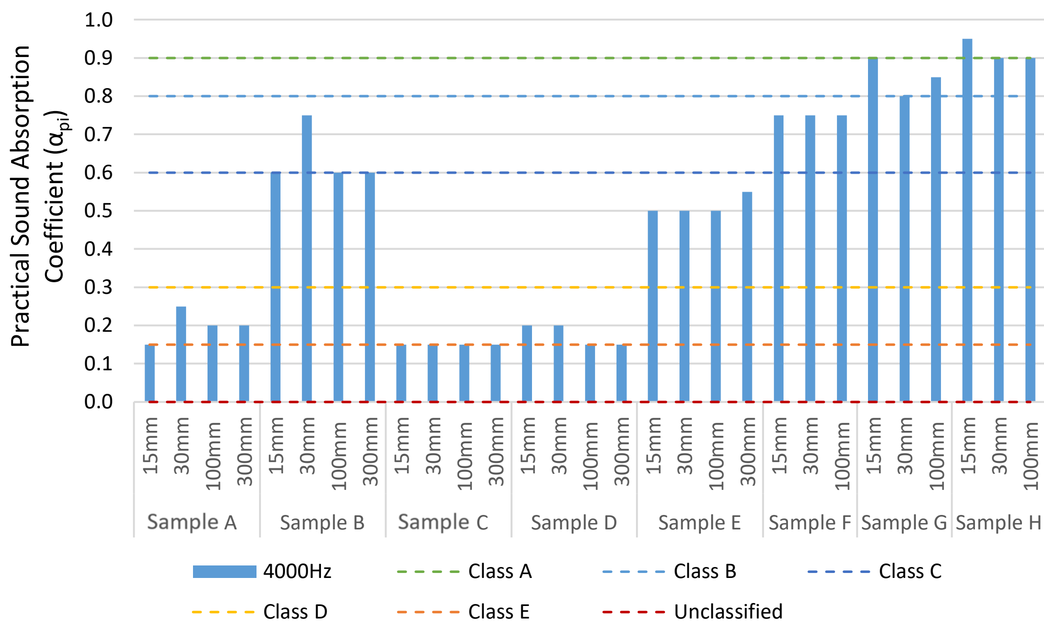

Figure 133. Practical Sound Absorption Coefficient (α_{pi}) for all samples tested at all mounting distances at 4000 Hz.

Figure 133 identifies that all eight samples effectively absorbed sound and achieved a $\alpha_{pi} \geq 0.15$, equivalent to a Class E or better rating at 4000 Hz. Sample H performed best achieving a α_{pi} of 0.95, equivalent to a Class A when mounted at 15 mm. Increasing the mounting distance consistently improved the α_{pi} for 1 of the 8 samples at 4000 Hz.

The way the mounting distance affected the α_{pi} at 4000 Hz can be summarised as:

- Between 15 and 30 mm, two of the eight samples α_{pi} increased and two of the eight samples α_{pi} decreased. The remaining four samples had the same α_{pi} between the distances.
- Between 30 and 100 mm, four of the eight samples tested had the same α_{pi}. Three of the eight samples tested α_{pi} decreased between the two distances and the remaining sample (Sample G) α_{pi} increased between the distances.
- Between 100 and 300 mm, four of the five samples α_{pi} stayed the same. The remaining samples α_{pi} increased between the distances.

5.4.2.3 Weighted Sound Absorption, α_w

Figure 134 plots the Weighted Sound Absorption Coefficients (α_w) by sample and mounting distance. Overall, the honeycomb structured fabrics, Sample G (α_w = 0.50, Class D) and H (α_w = 0.55, Class D) were the most effective across all distances. However, the flat fabrics Sample B and E were almost as effective, when Sample B was mounted at 100 mm it had a α_w of 0.45 (Class D) and Sample E achieved a α_w = 0.25 (Class E) when mounted at 30 mm.

The way the mounting distance affected the α_w can be summarised as:

- Between 15 and 30 mm, seven of the eight samples tested improved in α_w between the two distances and one of the eight samples (Sample F) did not change.
- Between 30 and 100 mm, six of the eight samples tested improved in α_w between the two distances. Two of the eight samples (Sample C and D) tested decreased in α_w between the two distances.
- Between 100 and 300 mm, three of the five samples (Samples B, C and D) tested improved in α_w between the two distances, one of the five samples (Sample A) had the same α_w between the distances and the remaining sample (Sample E) decreased in α_w between the two distances.

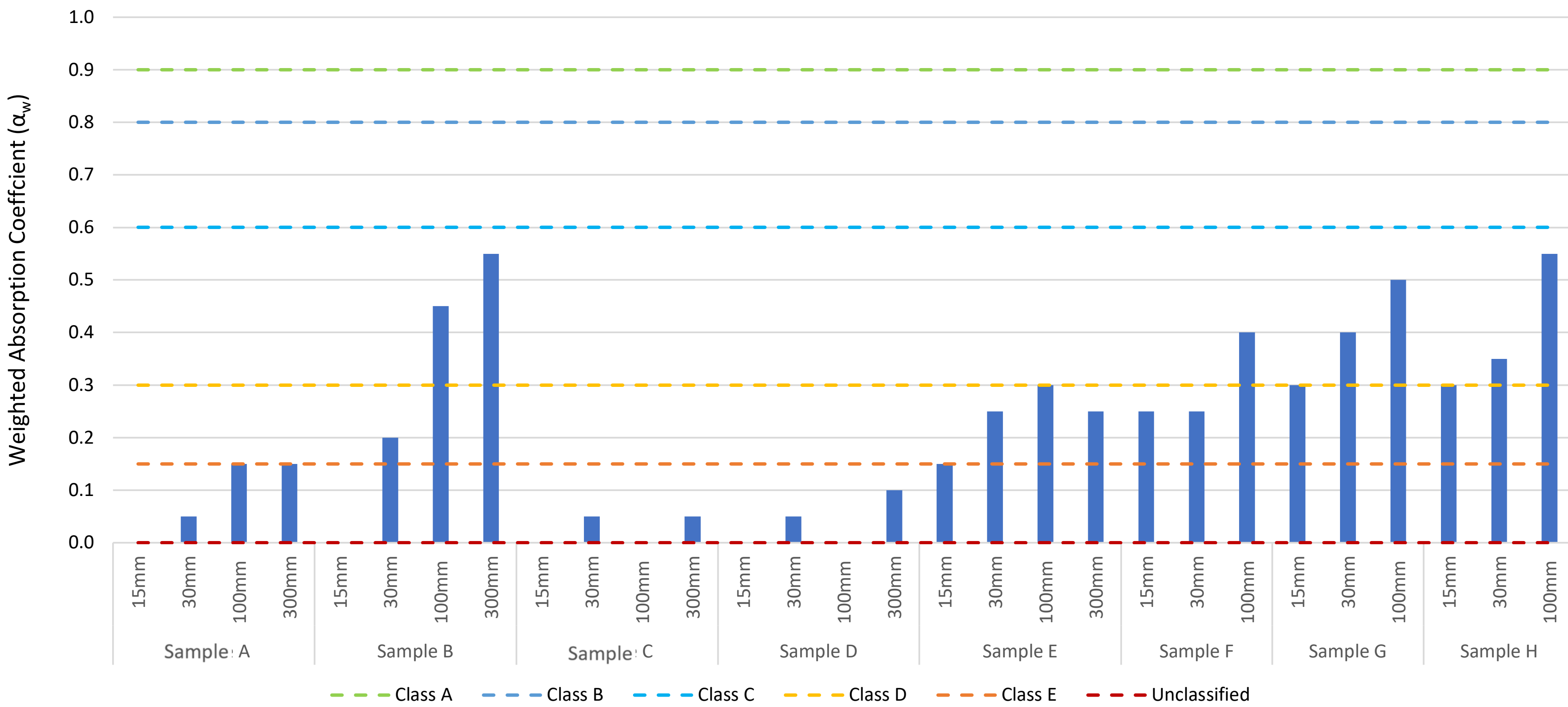

Figure 134. Weighted Sound Absorption (α_w) of each sample at differing mounting distances.

5.4.2.4 ISO Class

The ISO Classes presented in 0 and displayed in Figure 121 - Figure 128 identified that two of the flat fabrics (Sample C and D) were 'Not Classified' across the mounting distances. The remaining flat fabrics (Sample A, B and E) varied in performance. Two of the samples improved in performance as the mounting distance increased (Sample A and B), Sample A varied between 'Not Classified' and Class E where Sample B varied between 'Not Classified' and Class D. The remaining flat fabric (Sample E) varied in performance between a Class D and E with a peak α_w of 0.30 when mounted at 100 mm. The honeycomb Sample F improved in performance as the distance increased between Class D to Class E. Sample G and H consistently performed at a Class D level between 15 and 100 mm mounting distances.

5.4.2.5 Predicted Reverberation Time (RT) of a Office With and Without Shading

The calculation method set out in Section 5.4.1.2 (p. 335) was applied to the case study office examined in Chapter 4 to predict the RT and RT_{mf} of a room with and without shading extended at the window. In summary the method requires absorption coefficients of the materials used as surface finishes within the room, the surface area of each material, and the volume of the room to be able to predict both the RT and RT_{mf}.

The open-plan office in Chapter 4 has a total volume of 110.11m^3 (7.7m L x 5.5m W x 2.2m H). The office had three windows with a total glazing surface area of 5.65m^2. For the purposes of this acoustic evaluation the secondary glazing of the case study office was theoretically replaced with double glazing which are more commonly installed in UK buildings. The room surfaces were assumed to be constructed of standard brickwork, the ceiling finished with a decorative plaster and the flooring covered by a 9mm tufted carpet. Acoustic material data (α_{pi} and α_w) for the surfaces within the room were supplied by the Building Research Establishment. This data was also used in the creation of BB93 Acoustic Design of Schools: performance standard (DfE, 2015)[51]. The absorption coefficients previously calculated for Sample H (when mounted at 100 mm) were integrated into the assessment (α_w = 0.55, Class D). Sample H was selected as it was the best performing fabric across all frequency bands in terms of sound absorption. The surface area of the fabric was assumed to be equivalent to the surface area of the glazing area.

Table 60 and 61 present the α_{pi} and the α_w for all the surface materials within the unoccupied and unfurnished office. Table 60 presents the results for the 'without shading' scenario and provides the calculated RT based on the α_{pi}, the α_w, and the RT_{mf} (the average RT of the mid-frequency octave bands for 500, 1000 and 2000 Hz) when there is no shading installed. Table 61 presents

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[51] These values and other typical acoustic performance values are provided in Section 5.2.2 (p. 305).

Table 60. Predicted Reverberation Time (RT) of the case study office without shading.

Material	Surface Area (m^2)	α_{pi}					α_w	α_A (α_{pi} x A)					α_{Aw} (α_w x A)
		250	500	1000	2000	4000		250	500	1000	2000	4000	
Walls - Standard Brickwork	67.06	0.04	0.02	0.04	0.05	0.05	0.05	2.68	1.34	2.68	3.35	3.35	3.35
Floor - 9 mm pile carpet, tufted on felt underlay.	42.35	0.08	0.30	0.6	0.75	0.8	0.35	3.39	12.71	25.41	31.76	33.88	14.82
Ceiling - Plaster (Decorative Panels)	42.35	0.22	0.18	0.15	0.15	0.16	0.15	9.32	7.62	6.35	6.35	6.78	6.35
Window - Double glazing, 2-3 mm glass, 10 mm air gap	5.65	0.05	0.03	0.03	0.02	0.02	0.02	0.28	0.17	0.17	0.11	0.11	0.11
Total Surface Area (m^2)	157.41			$\alpha_{A, TOTAL}$				15.67	21.84	34.61	41.58	44.12	24.64
				Reverberation Time (RT) =				1.12	0.81	0.51	0.42	0.40	0.71
											RT_{mf} =		0.58

Table 61. Predicted Reverberation Time (RT) of the case study office with shading.

Material	Surface Area (m^2)	α_{pi}					α_w	α_A (α_{pi} x A)					α_{Aw} (α_w x A)
		250	500	1000	2000	4000		250	500	1000	2000	4000	
Walls - Standard Brickwork	67.06	0.04	0.02	0.04	0.05	0.05	0.05	2.68	1.34	2.68	3.35	3.35	3.35
Floor - 9 mm pile carpet, tufted on felt underlay.	42.35	0.08	0.30	0.60	0.75	0.80	0.35	3.39	12.71	25.41	31.76	33.88	14.82
Ceiling - Plaster (Decorative Panels)	42.35	0.22	0.18	0.15	0.15	0.16	0.15	9.32	7.62	6.35	6.35	6.78	6.35
Blinds - Sample H at 100mm	5.65	0.25	0.6	0.85	0.75	0.90	0.55	1.41	3.39	4.80	4.24	5.09	3.11
Total Surface Area (m^2)	157.41			$\alpha_{A, TOTAL}$				16.80	25.06	39.25	45.71	49.10	27.64
				Reverberation Time (RT) =				1.05	0.70	0.45	0.39	0.36	0.64
											RT_{mf} =		0.51

the results for the ‘with shading’ scenario.

The results from Table 60 identify that covering the glazing with a shading fabric can reduce the RT in each one-third octave band by between 0.03 and 0.11 seconds. Based on the α_w a RT reduction of 0.07 seconds is provided by installing and extending the shading fabric. Lastly the RT_{mf}, the criteria used in acoustic design guidance for schools, identifies that both rooms met the < 1 RT_{mf} requirement however when shading was included the RT_{mf} reduced by 0.07 seconds.

5.4.3 Discussion

This study has shown that mounting shading products at smaller distances (< 100 mm) can significantly affect the absorptive properties of the shading fabrics. Overall, the mounting distances differed the α_w by between 0.05 and 0.55 but this varied depending on the fabric sample being tested. The Sample B fabric was most sensitive to the mounting distance performing best (α_w = 0.55) when mounted 300 mm from a glazing surface and performing worse when mounted at 15 mm (α_w = 0.00). Sample C performed poorly regardless of what mounting distance was tested as the α_w only differed by 0.05 across the distances tested. The researcher chose the distances tested to reflect that of real-world installation practices[52]. Whilst these distances were chosen there may be some discrepancies when relating the data to real-world installations. Further research should look at identifying ‘typical’ mounting distances for differing shading products and systems (e.g., internal free-hanging roller blinds, internal zipped roller blinds etc.). Products could then be tested at these distances which would have more relevance to real-world installation practices and allow products to be benchmarked and compared against one another more robustly. It is also worth noting that it is suggested within BS EN ISO 354 (BSI, 2003) that there will be relatively little difference in absorption performance when samples are tested at distances > 300 mm.

When reviewing the α_w properties of the shading fabrics an optimum mounting distance was identified for one of the eight fabrics assessed. Sample E performed best at 100 mm (α_w = 0.30) and slightly worse at 30 and 300 mm (α_w = 0.25), suggesting that this fabric would perform best when installed outside of the window reveal. Sample C and D revealed a bi-modal pattern of performance across the distances tested and both performed better

[52] 15mm reflected an internal blind installed as part of a zipped system (which is fixed to the window frame), 30mm reflecting an internal blind positioned inside the window reveal, 100mm reflecting shading installed outside of the window reveal and 300mm reflecting shading products installed as a sail.

when either installed at 30 mm or 300 mm. The remaining four samples (A, B, F - H) improved in their ability to absorb sound as the distance from the window increased, suggesting that an optimum distance had not been identified, however this can only be confirmed with further testing of distances > 300 mm.

The bi-modal performance of Sample C and D can be better understood by reviewing the α_{pi}. The α_{pi} results at 30 mm identify that the samples reduced higher frequency sound more effectively where at 300 mm the samples were more effective at reducing lower frequency sound. This performance outcome would be hidden by the resulting α_w more frequently reported. However, if the difference in absorption was greater than 0.25 from the reference curve this would have been identified by the associated shape indicator. Though, in this case the differences were < 0.25. This supports that supplying α_w data alone may be insufficient for acousticians to carry out a detailed acoustic analysis. Supplying α_{pi} data in addition to α_w can be a great benefit to acousticians whilst α_w is useful for quick product comparisons (Peters et al*.,* 2011).

The α_{pi} related to low frequency sound (250 Hz) either increased or remained the same as the mounting distance increased for all fabrics. A similar result was found for the mid-frequency α_{pi} octave bands (500 Hz and 1000 Hz), although Sample B and E had one α_{pi} that decreased between 100 and 300mm[53]. The α_{pi} for high frequencies (2000 and 4000 Hz) of sound peaked at smaller mounting distances either 15 or 30 mm. This suggests that a smaller mounting distance is more beneficial for absorbing higher frequency sound, where installing shading products further away from the window is more beneficial for absorbing low and mid frequency sound. Interestingly all shading fabrics α_{pi} altered in a similar way when the mounting distance was increased, however the magnitude of the variation in α_{pi} varied between the fabrics tested. Based on these results the mounting distance for shading fabrics could be potentially chosen based on the frequency of sound that requires absorbing. Lower frequencies of sound are believed to be more problematic to attenuate thus installing shading products further away from glazed surfaces could provide an acoustic benefit in certain situations (Peters et al*.*, 2011).

The acquisition of shading product data (α_w and α_{pi}) and the inclusion of this data in the method derived from Sabines Formulae and explained within Peters et al*.* (2011) enabled an early-design assessment of the acoustic reverberation time within the case study office to be carried out inclusive of shading. The best performing fabric within the absorption

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[53] For Sample B this was at 500 Hz and for Sample E this was at 1000 Hz.

testing (Sample H) demonstrated that it could help reduce the RT and RT_{mf} by 0.07 s when fully extended. The magnitude of the RT reduction will vary depending on the extension of the blind, overall volume of the room, the surface area and acoustic absorption properties of the other surface materials used in the room. Further iterations of room designs (including differing shading products and rooms with differing wall to window ratios) could identify a relationship between the area of shading fabric and the reduction in reverberation time. In future work, this method of theoretically assessing the impact of shading on the RT and RT_{mf} should also be validated against real world measurements of the absorptive performance of shading products in-situ to identify if the way shading products are mounted impacts the absorptive properties. This further work should also put into context how the inclusion of absorptive shading products compares with other methods of improving the acoustic absorption within a room (e.g., specifying a different thickness of carpet, more absorptive furniture, and ceiling coverings).

Additionally, whilst the case study example provides a method for including and evaluating the impact of shading on the RT of a room this type of analysis should be carried out in conjunction with an evaluation of the subsequent thermal and visual impact of having a blind closed on occupant comfort. For example, in the case study example the reality of Sample H being used as a method of achieving the desired reverberation time would mean compromising an occupants' visual comfort as the shading product would obstruct natural daylight and views out. This is unlikely to be tolerated by occupants, particularly within an office environment.

The study described is also limited by the narrow selection of shading products tested as the study only tested and analysed a select number of internal free-hanging shading products. Nevertheless, these products are commonly installed in both residential and non-residential buildings in the UK. Tensioned and guided or zipped systems (where the blind fabric is enclosed in a channel fixed to the window frame) would likely differ in acoustic absorption performance and would need to be tested to identify whether they perform in a similar way to free-hanging shading products.

5.5 Sound Transmission and the Acoustic Absorption Properties of Shading Fabrics

The results produced relating to the absorptive and sound transmission properties of the shading fabrics tested that are conventionally used internally in UK buildings are presented in Table 62. This table presents the α_w and associated ISO Class of the fabrics when mounted at a 30 mm distance representative of a shading fabric installed within the window reveal and the R_w and adapted R_w for living activity noise (C) and low frequency noise (C_{tr}).

Table 62. Acoustic Absorption and Sound Transmission Properties of Shading Fabrics

Sample	Acoustic Absorption Properties (at 30 mm mounting distance)						Sound Transmission Properties (dB)		
	α_{pi}				α_w	ISO Class	R_w	$R_w + C$	$R_w + C_{tr}$
	250 Hz	500 Hz	1000 Hz	1500 Hz					
A	0.00	0.00	0.05	0.20	0.05	No Class	1	-	-
B	0.00	0.10	0.25	0.60	0.20	E	5	5	4
C	0.00	0.00	0.05	0.10	0.05	No Class	1	-	-
D	0.00	0.00	0.05	0.15	0.05	No Class	2	-	-
E	0.05	0.15	0.50	0.55	0.25	E	10	9	8
F	0.05	0.15	0.40	0.70	0.25	E	-	-	-
G	0.15	0.35	0.70	0.85	0.40	D	-	-	-
H	0.10	0.30	0.60	0.90	0.35	D	-	-	-

When comparing the α_w and associated ISO Class of the fabrics with the R_w of Samples A - E it can be observed that there is a positive relationship between the effectiveness of the fabrics as an absorber of sound with how effective they are at reducing sound from transmitting into a building. Sample B and E are most effective at absorbing sound and reducing sound from transmitting into a building. Interestingly a 0.05 increase in the α_w corresponded with a 5 dB increase in R_w, suggesting a linear relationship but more data would be needed to confirm this relationship.

5.6 Summary

The results of this study provide indicative results that suggest that the properties of shading fabrics used internally and typically used in UK buildings vary the amount of sound that is transmitted through them or absorbed by them. This research supports previous literature in identifying that shading fabrics are generally better at attenuating sound at higher frequencies as opposed to lower frequencies.

The amount of sound reduction provided by the shading fabrics tested in this study exceeds the amount of sound reduction previously identified in other academic work. However, as the test methods in this study concentrated on the sound reduction performance of the fabric alone as opposed to a fully installed shading system, further work should be carried out that identifies whether the level of sound reduction performance is impacted when installed and assessed in a full shading system. The extent of the sound absorption provided by shading fabrics was also identified and these results suggest that this varies depending on the properties of the shading fabric tested e.g., structure, material, weight, surface area. Further systematic testing is needed to identify more robustly the attributes of shading fabrics that contribute to improvements in sound absorption and further investigation should consider how the surface finish (e.g., fibrous, or smooth) and the structure of the weave influences their performance. Additionally, it has also been identified that the absorption of sound is impacted by the distance that the shading product is mounted away from a window. When shading fabrics are positioned further away from the window the absorption of sound at lower frequencies increases but the absorption of sound at higher frequencies is reduced. Given that lower sound frequencies are often more problematic to attenuate in certain circumstances it would be beneficial to install shading products outside of the window reveal. For example, when installing shading products in bedrooms where external traffic noise may cause sleep disturbances as shading products are more frequently extended in bedrooms at night.

The ASTM E2611 - 17 (ASTM International, 2017) method of assessing the transmission of sound by fabrics could prove beneficial for the shading industry as it provides a quick and cheap method of testing the acoustic reduction properties of shading fabrics enabling manufacturers and consumers to quickly compare the sound reduction performance of different fabrics against one another more easily. However, improvements are still needed within the methodology to ensure shading fabrics of all structures can be tested and compared, or potentially a new method needs to be developed.

The methodology outlined by Peters et al*.* (2011) was used to identify the impact a shading fabric can have on the reverberation time within a room. Further work should look to corroborate this theoretical assessment by conducting a real-world assessment of a specific fabric in a room with the theoretical method. The ability to include the absorptive properties of shading fabrics in the early design of a building by acousticians could assist in reducing the requirement for alternative or additional sound absorbency control measures.

The shading industry produces a large range of fabrics made of different materials, with various coatings, differing thicknesses, weights, structures, weaves, and opaqueness that result in fabrics that fulfil the different aesthetics, visual and thermal requirements consumers require. To fulfil the thermal and visual requirements defining the fabric properties has been instrumental in their uptake within building design. It is therefore likely that the increased availability of data relating to the acoustic properties will also be beneficial for the industry. However, the acoustic comfort benefit will only be perceived by occupants if shading devices are extended. When shading devices are closed, they will also have a subsequent impact on the thermal and visual comfort of occupants. Therefore, a trade-off is required if acoustic comfort is to be obtained through using shading devices. This may be problematic for occupants if it is relied upon as a strategy for acoustic comfort during the daytime however it may be less of an issue for occupants at night when occupants prefer both darker and quieter internal conditions (for sleeping) which can both be achieved when blinds are closed.

CHAPTER 6. LIFE CYCLE ASSESSMENT

6.1 Overview

Manual solar shading products are a passive measure that can be operated to attenuate excessive solar gain entering a building and used in colder months to further insulate the façade preventing heat losses. These products can also provide electric lighting savings if opened and closed appropriately to utilise natural daylight. Therefore, the systems can be operated to provide heating, cooling and electric lighting energy savings (ES-SO, 2018b; Littlefair, 2017b). However, manual shading systems are not always opened and closed efficiently to save energy. Innovations in shading products, such as motorised and automatic shading systems, can help increase the frequency of blind movements. The installation of motorised systems can encourage user interaction with shading products thus increasing the number of times they are opened and closed within a day (Littlefair et al., 2010; Paule et al., 2015). Automated systems can be set up so they extend and retract based on internal or external environment conditions autonomously (BRE, 2017; Foldbjerg and Christoffersen, 2015; Lee et al., 2013). Integrating motorised and automated shading systems can help provide greater energy savings than traditional manual shading systems (Foldbjerg and Christoffersen, 2015; Littlefair et al., 2010; Paule et al., 2015). The overall environmental impact (operational and embodied environmental impact) of these shading systems is unknown. Most studies consider either the operational energy benefit of shading products and/or carbon equivalent inputs or outputs (Andrews et al., 2015, 2017; Babaizadeh et al., 2015; Dubois, 1998b, 1997, 2001; ES-SO, 2014; Hutchins, 2015; PHYSIBEL, 2005; Seguro and Palmer, 2016; Wouter et al., 2010; Ylitalo et al., 2006a, 2012) even though Life Cycle Assessments (LCAs) provide a more comprehensive means of assessing the environmental impact of a product and its subsequent effect on the surrounding environment.

To carry out an LCA the environmental impact of each stage of a products life cycle is assessed – from “cradle to cradle” or “cradle to grave”. Manufacturers can provide details on the components used within differing shading systems, and the way shading systems are assembled makes them relatively easy to disassemble and analyse the materials and manufacturing processes used (BSI, 2018). However, where a product is finally installed, how it is used (opened and closed), and how they affect the energy consumption of buildings, is more complex to predict or know. Additionally, the products lifespan and what happens to the product at the end of the product’s lifetime is uncertain as these decisions are made by either the end-user or consumer of the shading product. The studies that have carried out LCAs on manual shading products have found that there is a significant difference in environmental impact depending on whether a product is recycled at the end of its life or sent to landfill (Andrews et al., 2015, 2017; Ylitalo et al., 2006b). The uncertainties of how differing shading products are operated, how much energy they save, and how long shading products are installed for, means that these variables within an LCA either need to be assumed or they need to be investigated by systematically varying the input variables to identify the point at which differing shading products become environmentally beneficial. Systematic investigation enables the environmental impact of differing shading product systems to be compared against one another.

This study builds on the previous work that has assessed the environmental impact of manual and motorised blinds in a typical semi-detached domestic home in the UK (Andrews et al., 2015, 2017). The research evaluates the life-time environmental impact of three differing shading systems: - internal manual roller blinds, internal motorised roller blinds and external automated venetian blinds. The study identifies the number of years these systems need to be installed for and the amount of operational energy that needs to be saved before they can be considered environmentally beneficial. This is done by stepping the operational energy savings and evaluating the environmental impact over the course of the product lifetimes. The investigation is limited by the two end-of-life scenarios explored. The first represents a best-case scenario which considers the re-use of shading product components and recycling of waste materials, and this is compared with a worst-case scenario where waste materials are sent to landfill.

The operational energy savings provided by the various shading systems modelled are based on research literature that identified that shading products could save up to 15% of the heating energy required to heat a building. This literature was reviewed in depth in Chapter 2, Section 2.3.4. The current amount of heating energy used in a typical semi-detached domestic home in the UK (6, 696 kWh per annum) (DECC, 2013) suggests that the use and installation of shading could provide approximately 1,000 kWh energy saving per annum. However, the energy savings provided by shading products are highly variable as they are influenced by the specifics of a building design, how shading products are used (which is affected by human behaviour) and the thermal properties of the shading products themselves. The thermal properties of shading products are wide ranging and not often considered when selected to be installed in a domestic home in the UK. Often other factors such as their ability to provide privacy, room darkening, and their aesthetic are prioritised. Therefore, the operational energy savings have been stepped between 5 and 20% to determine the point at which the operational energy savings start to provide an environmental benefit. The study has also considered what the future operational energy use of a UK home may be if cooling energy was additionally required to maintain thermal comfort in warmer weather periods. A recent report has predicted that the energy required for air conditioning in a semi-detached home in a moderately warm summer year would be 1,192 kWh per annum (MHCLG, 2019b, 2019c). For this assessment only one shading system has been assessed - an automated external shading system - and the same operational energy saving steps have been considered (between 5 - 20%).

6.2 Study Context

In the UK internal manual shading systems are most frequently installed within domestic homes and there is a growing demand for internal motorised shading devices. Technological advances have made the price of motors and control systems relatively cheap. Control interfaces can now be integrated into smartphones or smart home management tools making shading products easier to use and operate even when away from the building (Littlefair, 2017a; Seguro and Palmer, 2016; Somfy, 2021). A more recent innovation, automated shading systems, are growing in popularity across Europe. In the UK automated systems are commonly installed in non-domestic buildings and are recommended for un-owned and unmanaged spaces (like foyers). However, some systems have been installed into a select number of smart homes within the UK and have been found beneficial in providing energy savings in combination with other smart control systems (BRE, 2017; Foldbjerg and Christoffersen, 2015).

Within Europe automated systems are being encouraged within the recast of the Energy Performance Building Directive because of the increase in energy savings smart controls can provide (BPIE, 2019; ES-SO, 2018b). Automated systems are also more likely to operate in line with energy modelling simulations which incorporate a specified opening and closing strategy for shading products. Building energy modelling simulations use similar metrics (i.e., the external and internal environment conditions) that automated shading systems use in the configuration of their control algorithms (BRE, 2017). Even though automated shading products may provide greater operational energy savings, automated shading systems require more materials (e.g., electronics, wiring and sensors) which require more complex manufacturing processes as well as electrical input for them to operate. Therefore, these systems will likely have a greater operational and embodied impact than that of manual and motorised shading systems. It is therefore important that automated shading systems are robustly assessed to identify whether the additional complexity of the componentry, the additional materials used within them, the operational energy they require, and the end-of-life scenario associated with these product systems will be offset by the additional operational energy savings these systems can provide. This will help assess the environmental viability of these systems when compared to more traditional shading systems.

As mentioned previously, internal shading products are more frequently installed in UK homes however, it is likely that in the future domestic homes in the UK will need to integrate external shading systems to avoid overheating in warmer weather periods. Several studies have assessed the operational energy impact associated with both internal and external shading products (Dubois, 1998a, 1997, 2001; Hutchins, 2015; PHYSIBEL, 2005; Seguro and Palmer, 2016; Wouter et al., 2010). These studies have shown that external shading products are more effective at reducing cooling energy than heating energy. However, in some cases, the extension of either internal or external shading increased heating demand. When shading products are extended (closed) during daylight hours they can block valuable solar gains which help heat up internal spaces. Nevertheless, in the cooling season, external shading systems are most effective at reducing cooling demand when extended during daylight hours.

Therefore, this study sets out to compare the environmental impact of three shading systems: internal manual, internal motorised and external automated shading systems. To identify the environmental impact of systems currently installed, those that are growing in popularity and those that may be more sought after because of climate change. The three systems were assessed based on them being installed in a semi-detached house in the UK that required either heating energy alone or heating and cooling energy to maintain thermal comfort. For simplicity, this study has not considered the impact shading products may have on electrical lighting energy consumption or incorporated the embodied environmental impact of air conditioning or heating systems and has instead focused on the energy consumed by heating and cooling systems.

6.3 LCA Methodology and Analysis

The type of LCA carried out in this study was a screening LCA using the Eco-Indicator 99 method produced with Sima Pro software and the Ecoinvent database which uses a hierarchical (average) weighting set. Screening LCAs provide a rough estimation and assessment of environmental impacts by considering the most relevant materials and resources using average data (ifu Hamburg, 2021). The weighting set simplifies the various environmental impacts of products into Ecopoints so that the impacts can be easily compared. 1,000 Ecopoints or 1 million milli-points (mPt) represents the average environmental impact of 1 European person per year (Ministry of Housing, 2000).

Within this LCA process the first step was to collect data and environmental information about the various stages in the shading products life cycle and use this data to calculate the environmental impact for these stages. The stages considered in this screening LCA are: - raw material extraction, bulk material processing, component manufacture, product assembly, installation with transport, product in use (or operation energy use), and treatment at end-of-life which are illustrated in Figure 135.

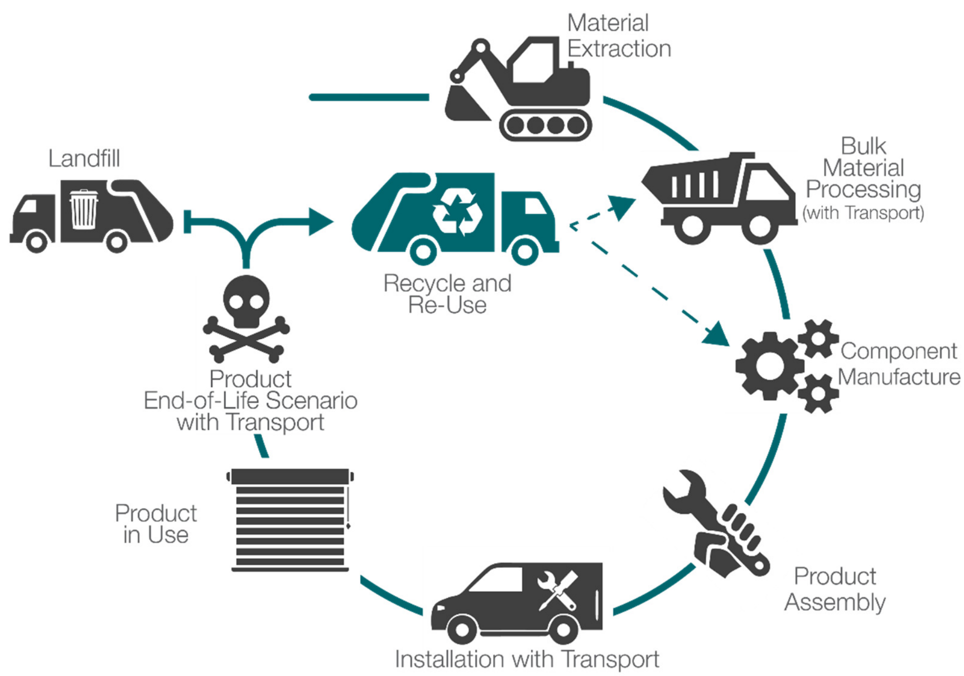

Figure 135. Life Cycle Assessment stages for shading products

To calculate the environmental impact of the ‘product in use’, also referred to as the ‘operational energy use’, a ‘functional unit’ needed to be defined and further information relating to the functional unit needed to be collected. For the purposes of this study the functional unit was based on a typical semi-detached domestic house. Information related to the size and number of windows and shading products and the energy required to heat and cool the home when there were no shading products installed needed to be determined. The next step was to produce the LCA models based on the information collected regarding the functional unit. Two baseline models that represented the ‘without shading’ scenarios were produced. These two models differed by the type of energy required to maintain thermal comfort in the functional unit. One required only heating energy and the other heating and cooling energy to maintain thermal comfort. Three ‘with shading' models were also produced. These three models included the heating energy functional unit and differed only by the shading system included within the models. Each of the models included either the installation of manual internal roller blinds, motorised internal roller blinds or external automated venetian blinds to all the windows in the home. A further 'with shading' model was produced that included the heating and cooling energy functional unit and the installation of external automated venetian blinds. In existing homes often, a variety of different shading systems (e.g., a mix of manual, motorised, and automated systems) and products (e.g., a mix of venetian, roller, vertical, awning etc.) are installed in/on buildings but for simplicity and for the purposes of the study only one shading system and product type has been applied to all the windows throughout the functional unit. The last step was to compare the environmental impact of the baseline 'without shading' models with the 'with shading' variant models produced. This data was then interpreted to identify how long it would take each shading system to offset the environmental impact of the product against the operational energy savings throughout the products lifetime. Comparisons were made between the shading system types to identify which system offset the environmental impact the quickest and how the operational energy savings and the end-of-life scenario affected the length of time needed to offset the environmental impact of the product system.

6.3.1 Functional Unit and Base Case Models

The functional unit in this screening LCA was a semi-detached domestic house which is representative of 26% of the UK housing stock (MHCLG, 2019a). The design of the functional unit was based on a simplified design of the semi-detached house presented in Case Study 2 in Chapter 3. The house had seven windows, totalling to 14.5m^2 of glazing, that would require blinds to cover them. To simplify the model each window was assumed to be of equal size and therefore each blind is also assumed to be equal in size. Seven windows and blinds, further referred to as window systems, are split across two façades (SW/NE). The models considered two window systems on both façades on the first floor, two on the NE façade on the ground floor, and one window system on the SW façade on the ground floor.

In the UK, the average annual energy consumption for space heating is 60% of total domestic energy use (although this is known to vary according to external air temperatures). The energy use for domestic heating in this study was based on the total household end use of 11,160 kWh per annum (DECC, 2013), equating to 6,696 kWh per annum. A typical UK generation mix that includes various fossil fuels and renewable technologies was used to calculate the environmental impact of the heating energy required. 6,696 kWh per annum which equates to 205.4 mPt per annum which represents the environmental impact of the 'without shading' model when heating energy was required to maintain thermally warm and comfortable temperatures in the functional unit.

A recent report published by Ministry of Housing, Communities and Local Government (MHCLG, 2019c) predicts that the future energy requirement for an average residential house for air conditioning will be 1,192 kWh per annum per household[54]. The same typical UK generation mix was used to calculate the environmental impact of 1,192 kWh per annum which equated to 36.6 mPt per annum. For heating, the same heating energy requirement was considered in the heating energy model although in reality this may be less as climate change will not only increase external air temperatures in summer but will also increase external temperatures in the heating season (Jenkins et al., 2009; Kendon et al., 2020). Therefore, the environmental impact of the 'without shading' model where both heating and cooling energy was included to maintain thermally comfortable conditions all year round equated to 242 mPt.

6.3.2 Shading Product Rationale

In both internal shading models (manual and motorised), the environmental impact of roller blinds was assessed. Roller blinds are a popular product used in domestic homes and are versatile as differing fabrics can be selected depending on the uses of a room and preferences of the users. Dimout fabrics (fabrics with a low visible light transmittance, τ_v) are conventionally installed in rooms that either require room darkening or privacy (e.g., bedrooms or bathrooms) and fabrics with a higher τ_v are selected for living spaces where more natural daylight is often wanted.

External aluminium venetians and external roller shutters have some of the lowest solar energy transmittance values (g_{tot} 0.03 - 0.15) of all external shading products (ES-SO, 2018a). Of these two product types, venetians are more adaptable as they can be tilted in various positions to either prevent solar gain (e.g., when tilted closed) or to attenuate and redirect light deeper within the building (e.g., when tilted at a 45° angle). When roller shutters are extended generally very little daylight is transmitted through them and the amount of daylight entering can only be increased by retracting the shutter. Currently roller shutters are more frequently used to improve the security of non-domestic properties and are infrequently installed on domestic homes in the UK. Therefore, external aluminium venetians were considered as the blind type in the external shading model.

[54]Value is based on the average modelled cooling energy required for a semi-detached home in three regions in England using DSY1 2020s weather data (MHCLG, 2019c)

6.3.3 LCA Models with Shading

The proceeding sections discuss what was included in the four 'with shading' models and Section 6.3.4 provides a summary of the inputs included in these LCA models.

6.3.3.1 Raw Material Extraction, Bulk Material Processing and Component Manufacture and Product Assembly

For each model data was collated about the weight and type of the materials used in each of the shading product systems and the manufacturing processes used to create the componentry and assemble the components together. This data was relatively easy to collect as the products lend themselves to be easily taken apart. The terminology used to define components in manual and motorised shading systems can be found in BS EN 122216 (BSI, 2018) and the British Blind and Shutter Associations' Training Guide (BBSA, 2016). Shading products are versatile in their componentry as there are common components that can be used in different types of shading products (e.g., roller blinds, cellular cell blinds, roman blinds). Secondary research sources from manufacturers (technical drawings and product information sheets) can also be used to determine materials, weights, and the quantity of components within a system. However, as most of the shading product componentry lend themselves to be easily deconstructed the products assessed in this study were disassembled and assessed.

6.3.3.1.1 Internal Manual Roller Shading System (ex. Fabric)

The manual roller blind that was reversed engineered and analysed is presented in Figure 136. The material makeup of the componentry includes polymers (nylon 6, acetal, PVC, and polyester), metals (aluminium, mild and stainless steel), paint and polyester cord. The manufacturing processes associated with the componentry included injection moulding, extrusion, sheet and bar production, metal forming and machining, yarn production and braiding and powder coating.

Figure 136. Disassembled manual polyester (dimout) shading system

6.3.3.1.2 Internal Motorised Roller Shading System (ex. Fabric)

When reviewing the available systems for motorised shading products a wide range of control systems and electronic component setups were found. To account for this product variation between motorised shading systems three control systems were assessed and the environmental impact of these three systems were averaged. These systems included:

- 1 x 'wand' control system which is attached to the blind system and operated using a push button,
- 1 x wall mounted remote control system,
- and 1 x portable handset remote control system.

For the two remote control systems each of the 7 blinds included in the model (to cover the 7 windows in the functional unit) was assumed to have one remote control based on a worst case scenario (Louvolite, 2017). The three control systems also differ in their electronic component setups. Two were operated with li-ion batteries and one system was hard-wired into the mains supply.

Motorised systems use many of the same components as manual shading systems. However, a number of additional components are needed. The additional components that are incorporated within the design of motorised shading systems are presented in Figure 137 - Figure 139. These new components included an array of additional polymers (glass filled nylon, rubber, HDPE, ABS, acrylic, silicone, PP, PVC), metals (copper, iron) and electronic components (PCB boards, batteries, copper wire, plug sockets) some of which required additional material processes that were also included into the model.

Figure 137. Additional components assessed for the 'wand' battery operated motorised system.

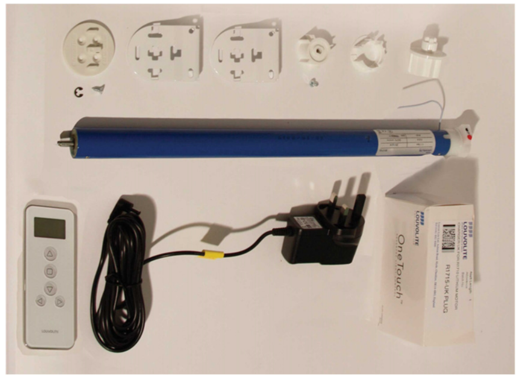

Figure 138. Additional components assessed for battery operated motorised system with portable handset.

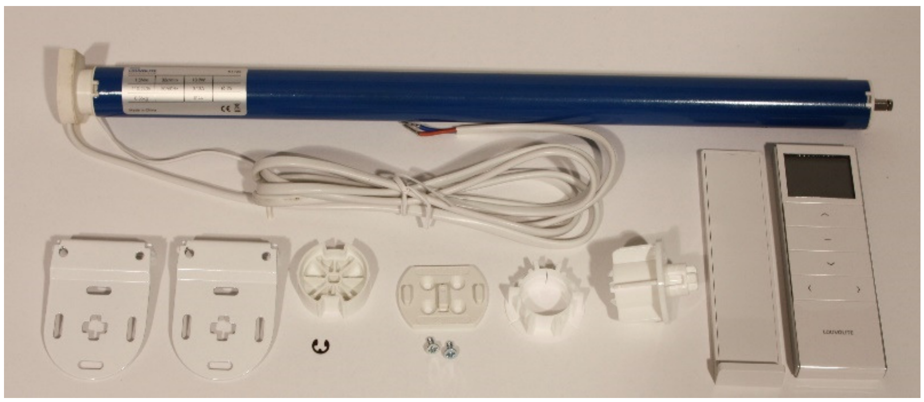

Figure 139. Additional components assessed for hard wired motorised system with wall mounted remote control.

Unlike the componentry of manual shading products those components that contained electrical elements were not easily disassembled and in some instances materials were difficult to separate (e.g., motors, PCB boards and copper wire with a PVC sheath). Precalculated environmental impact values are provided as part of the Ecoinvent database for some of these more complex components (e.g., pcb boards and electrical wire) however, other components required the use of hand tools to dismantle and assess them.

6.3.3.1.3 Fabric in Manual and Motorised Roller Blind Systems

The fabrics incorporated into a roller blind can vary in their material composition and visual and thermal properties. Therefore, within the models for internal shading products (manual and motorised models) the average environmental impact of three shading fabrics were included. The three fabrics that were averaged were two dimout fabrics (with low visible light transmission, τ_v, values) and one screen fabric (with a high τ_v value). The material composition of the fabrics that were averaged were:

- 100% polyester, multilayer dimout fabric,
- 72% PVC / 28% glass fibre composite dimout fabric,
- 64% PVC / 36% glass fibre composite screen fabric.

Prior to averaging the environmental impact of the three fabrics it was observed that the 100% polyester fabric had the lowest environmental impact, 1.03 mPt per blind when sent to landfill and 0.26 mPt per blind when recycled at end-of-life. The two composite fabrics had an environmental impact of 5.21 mPt and 4.42 mPt per blind when sent to landfill and 1.04 mPt and 0.88 mPt per blind when recycled at end-of-life. Of the two composite fabrics, the screen fabric had a lower mPt value when either recycled or sent to landfill at end-of-life. For all seven blinds the average environmental impact of the three fabrics was 18.66 mPt when sent to landfill and 3.81 mPt when recycled at end-of-life.

6.3.3.1.4 External Automated Venetian Shading Products

External shading systems are specifically designed to be durable to external weather conditions. The venetian slats, head bar and bottom bar and other smaller components are thicker, heavier, and thus stronger when compared to an internal shading product. Figure 140 shows the disassembled external venetian blind. The motor in this system is more robust than those used in internal motorised systems and requires more energy to operate the shading device due to the increased load the motor is under.

Figure 140. Disassembled external venetian shading product (excluding electrical components)

The model for the automated external venetian blind also included the componentry required for the automated system setup. The number of sensors, amount of wiring, and number of control interfaces vary between setups depending on the building layout, position of the blinds (internal or external, the number and position of windows, and the user's requirements. Most automated external shading systems incorporate wind sensors to ensure that shading devices are not extended when there are high external wind velocities that could potentially damage the product. Lux sensors can be positioned internally or externally and either placed close to or are attached to the window. These are often incorporated in automated systems to identify the lighting conditions and instigate blind movements based on these conditions. They can be set up to automate blind closures at night when conditions are dark and open when daylight is present (BRE, 2017). However, these settings can be altered depending on the occupants' preferences and vary between manufacturers. For example, if the occupant often suffers from overheating within their dwelling a lux sensor can be used so shading extends (closes) when it detects higher lux levels and retracts when there are darker conditions and lower lux levels measured. However, more commonly in the UK the former control system is implemented (i.e., shading products extend when low lux levels are detected and retract when there are higher lux levels to maximise the amount of natural daylight and solar gain let into a building).

More sophisticated automated systems incorporate a broader range of sensors such as air temperature sensors and pyranometers. However, these systems are more commonly used in commercial buildings. Algorithms used in automated systems can be implemented to consider all the data collected by these sensors in real-time or based on historical data collected. For example, some systems determine the season of the year by the external air temperature at a particular point in time in the day and implement a certain blind opening and closing algorithm based on this data (Gueguen et al., 2014). The greater the number of sensors required to collect data the greater the embodied and operational environmental impact of the shading system. However, these more advanced systems are also likely to be more accurate in predicting weather events and can adapt the façade efficiently to ensure the optimum energy savings are obtained through the appropriate positioning of shading. The algorithms can also be tailored to optimise occupant comfort through the monitoring of internal and external environment conditions.

In this study the automated shading setup was based on a remote transmitted system (RTS) and blind movements occurred based on a combined lux and wind sensor. However, the automated system also included a remote control override to allow flexibility in the system so occupants could override the automated blind movements when needed. Two remote controls were included in the model – one for each elevation of the building. The componentry of the two remotes was based on the environmental impact of the same two remote controls disassembled and analysed for the motorised system. 35 meters of copper cable with a PVC sheath (which linked the external motors and sensors to the mains supply), and the batteries needed to operate the sensors and remotes were also included in the model. The additional materials in this system included PU, PET, and hardened steel.

6.3.3.2 Transport

Transport can be factored into the LCA models at any lifecycle stage. This study has considered that often the assembly of shading products involves using components either produced in the UK or imported from China. Information supplied by manufacturers suggested that 25% of the components were imported from China. Therefore in all the shading models the environmental impact of transporting 25% of the components from from China was incorporated into the models and the remainder were assumed to be supplied and produced by UK manufacturers.

6.3.3.3 Operational Energy Use

The operational energy use is more complex to identify for shading products as the operational energy used is a result of how a shading product impacts the internal thermal and lighting conditions of a building. The energy consumed by a building is conventionally identified through conducting a building simulation using building simulation software. Iterations of simulations can be produced, and the operational energy use of various design iterations can be compared to identify the optimum building design for energy efficiency. Ylitalo et al. (2012) used a simulation software to identify the impact of an external roller blind on the energy required to heat and cool a room in a building in the UK and incorporated these energy outputs in a LCA. The simulation required a specific opening and closing control strategy to be applied to the shading products. The strategy chosen differed depending on the season of the year. 15% of the energy required to heat and cool the building was saved when compared to a simulation of the building without a shading product installed. The energy impact shading products have on buildings varies depending on the opening and closing strategy chosen (Da Silva et al., 2012) and whilst optimum strategies can be determined through creating iterations of building simulations there are no guarantees that occupants will operate shading products in the way they are implemented in building simulation tools. Furthermore, there is some concern that the impact of shading products are not accurately represented in all building simulation software systems (Gergaud and Liaros, 2018).

Within the Literature Review, Table 5 (Section 2.6.4., p. 45) summarises those studies that have evaluated the impact shading products have been reported to have on operational energy use through using building simulation tools. These studies have compared a building 'without shading' to a building 'with shading' and implemented a specific shading opening and closing strategy into these simulations. In all cases where heating and cooling energy is required to maintain the thermal comfort an energy saving benefit was provided through the installation and use of shading products. However, the energy saving benefit shading provided were specific to the buildings simulated and the parameters included within the simulations. Only one of the studies evaluated considered a UK climate and in this study between 5 - 40% of the total heating and cooling energy consumed was saved when a 'without shading' was compared to a 'with shading' model (Seguro and Palmer, 2016). However, this study was based on a cellular office that had a heavily glazed south orientated façade and thus was more susceptible to solar gains than the semi-detached house used in this study's functional unit. This means that the total energy savings are likely higher than those we would expect to find if we compared a 'with' and 'without shading' scenario in a semi-detached home. Additionally, the UK office study integrated a shading control strategy that did not differ between seasons (i.e., the same opening and closing strategy was used in winter months and summer months) and was operated to primarily prevent solar gain from heating the building internally. This resulted in a heating energy penalty because of the loss of daytime solar gains in the heating season (Dubois, 2001; Seguro and Palmer, 2016). The cooling demand reduced by 77% but the opening and closing strategy chosen caused the heating demand of the building to increase. Yet overall, there was still an energy saving provided as the cooling energy saving offset the heating energy increase. When seasonal control strategies were used to extend and retract the blinds both the heating and cooling energy demand reduced when the 'with shading' scenario was compared to the 'without shading' scenario in the studies evaluated in Table 5 (Dubois, 2001; PHYSIBEL, 2005; Wouter et al., 2010). In these studies, the impact shading products had on heating energy alone varied between 5 - 15%.

As previously mentioned, the heating only 'without shading' model includes 6,696 kWh per annum[55] in heating energy. This equates to an environmental impact of 205.4 mPt per annum. The energy savings that can be provided by the installation of shading are stepped between 5 - 20% based on the amount of energy savings that differing shading products have been identified to provide in the literature reviewed. This represents a reduction in operational energy use between 335 kWh (10.3 mPt) and 1,339 kWh (41.1 mPt) per annum. This means that for each year the shading products are installed and being used they will

[55] Based on the average amount of heating energy required in a semi-detached home in the UK (DECC, 2013)

have a positive environmental impact through reducing the amount of energy being consumed by the building. The energy savings were stepped to account for the fact that the operational energy saved by shading products are uncertain. Stepping the savings also means that the point at which installing shading becomes environmentally beneficial can be determined for the three differing shading systems which will vary in how effective they are in insulating the window.

For the heating and cooling 'without shading' model, an additional 1,192 kWh per annum, which relates to 36.6 mPt per annum was included in the model to account for the energy required for air conditioning[56]. Like the heating only model, the energy savings shading products could additionally provide were stepped between 5 - 20%. Even though shading products can save a greater percentage of cooling energy, as opposed to heating energy, the amount of cooling energy required is predicted to be several times smaller than the amount of heating energy needed to keep homes comfortable in winter. In this model the proportion of heating to cooling energy is an 85: 15 split. The 5 - 20% stepping of energy savings relates to a heating and cooling demand saving of 394 kWh (12.1 mPt) and 1,576 kWh (48.4 mPt) per annum.

Shading System Operational Energy

In addition to the operational energy of the functional unit the energy required to operate the shading systems was also included in the shading variant models. Manual shading products require no energy to operate them however motorised and automated systems do. For the motorised systems, the environmental impact of three systems were averaged together and so was the energy these three systems needed to operate. As previously mentioned, two of the three systems were operated by li-ion batteries, and one of the systems was mains operated (see Section 6.3.3.1.2). Battery charges typically last for 6 - 12 months depending on the level of use and so the model for the motorised systems included the electrical input for 1.5 charges per year. The mains operated systems electrical input requirement was calculated to ensure enough power was provided to raise and lower the blinds for 30 seconds twice a day. The mean of the electrical input required to operate the three differing types of motorised shading products assessed was calculated and the environmental impact of the electrical input was included in the motorised shading system model.

[56] Based on the average modelled cooling energy required for three differing building typologies in three regions in England using DSY 2020s weather data (MHCLG, 2019c)

For the external automated shading system, the electrical input required to operate the shading products was slightly greater than the electrical input required to operate the motorised products. This is because the external shading products and the motors are larger and therefore this system requires a greater amount of electrical energy to operate them when compared to internal motorised systems. The electrical input required was calculated on the same basis as the motorised blinds (i.e., raised and lowered twice per day for 30 seconds). Battery charges were also included in the model as batteries were needed in both the sensors and the remote controls in the automated system and similarly the electrical input for 1.5 charges per year were included in the model.

6.3.3.4 Product Lifetime, Maintenance and End-of-Life Scenario

Product Lifetime and Maintenance

Direct exposure to sunlight can cause some components to deteriorate and some fabrics can fade or discolour. This is estimated to occur after approximately 15 years according to industry experts (Attia, 2019). However, customers may want to replace internal fabrics when they redecorate, typically every five years. Manual blinds may be perceived as easier to simply replace. Therefore, a fabric 'refresh' (replacement) has been included in the model every 5 years for both internal shading systems. However, it is also believed that good quality blinds that are not misused or abused can last for more than 20 years (Andrews et al., 2017). Motorised shading systems are potentially more likely to undergo a 'fabric refresh' than manual blinds as the capital cost for motorised shading systems is greater. For simplicity in producing the models all components other than the fabric and batteries are reused (i.e., they continue to be used throughout the products 20-year lifetime). The fabrics and batteries are replaced once (at 5 years), twice (at 10 years), 3 times (at 15 years), and 4 times (at 20 years) over the product life for both manual and motorised blinds. Battery replacements were only included in the motorised and automated shading system models.

External venetian shading products are less likely to be replaced when redecorating but are more likely to be replaced due to damage from external weather conditions, often caused by strong winds. The likelihood of damage is reduced when the system is combined with a wind sensor as they are often programmed to retract the shading system when external wind speeds increase. Therefore, external venetian blinds have been assumed to have a 20 year lifetime based on anecdotal evidence from shading manufactures (Attia, 2019). After this length of time, it is also more likely that an external venetian blind with a powder coat finish may fade and start to look aged and need to be replaced for aesthetic reasons. The automated shading model in this study also includes a battery replacement every 5 years which were used within the remote controls and sensors.

End-of-Life Scenario

Treatment at end-of-life in LCAs can consider the products being either sent to landfill, reused, remanufactured, or recycled. It is currently unknown what happens to shading devices at end-of-life. If the products are not demounted, disassembled, and reused in the renovation or redecoration of a building then they may be left in-situ during the demolition of a building and sent to a construction or demolition landfill and used as municipal solid waste within landfills. Demolition waste is sometimes sorted for recyclable content before entering the landfill, but this is not always the case and more frequently demolition waste is sent to landfill without being sorted for recyclable content. Prior studies (Andrews et al., 2015, 2016, 2017) have conducted comparative screening LCAs of a variety of internal manual and motorised shading systems that are commonly installed in the UK. The benefit of recycling at end-of-life almost halved the environmental impact associated with sending the product to landfill at end-of-life which highlights the benefit of recycling. Similar conclusions were also reached by Ylitalo et al. (2012).

Even though it is possible to recycle shading products, as their componentry and how they are assembled means they can be easily taken apart at end-of-life, it can be difficult to find markets for some of the materials. This is particularly true for polymers. This means that reusing the components is an environmentally preferred option providing that the components are not worn or damaged. At present there is no legislation to support the recycling of manual blinds, but the inclusion of electrical and electronic components means that motorised and automated shading systems are subject to Waste Electrical and Electronic Equipment (WEEE) legislation (Office for Product Safety and Standards, 2018). These products should be disassembled and recycled at end-of-life. However, because of the uncertainties surrounding what happens to shading products at the end-of-life two end-of-life scenarios have been modelled representing a best and worst-case scenario. In the best-case 100% of the materials are recycled or reused and in the worst-case scenario the materials that need to be replaced are sent to landfill.

6.3.4 Model Summary

The previous sections have described what was included in each of the LCA models. The inputs in each of the 'with shading' models are summarised in Table 63.

Table 63. Model Summary of ‘with Shading’ LCA Model Inputs

	Heating Only Models			Heating & Cooling Model
	Internal Manual Roller Blind System	**Internal Motorised Roller Blind System**	**External Automated Venetian Blind System**	**External Automated Venetian Blind Shading**
Functional Unit / Base Cases				
Building Design:	SW orientation, Semi-detached domestic building with 7 x windows (14.5m^2 glazing)			
Heating Demand*:	6,690 kWh/yr (205.4 mPt/yr)			6,690 kWh/yr (205.4 mPt/yr)
Cooling Demand†:	-			1,192 kWh/yr (36.6 mPt/yr)
LCA Stages				
Raw Material Extraction to Product Assembly and Transport	7 x Internal Motorised Roller Blinds · Fabric of each roller blind is the average environmental impact of 3 x fabrics.	7 x Internal Motorised Roller Blinds · Fabric of each roller blind is the average environmental impact of 3 x fabrics. · System based on the average environmental impact of 3 x motorised systems.	7 x External Motorised Venetian Blinds · System includes: - 35 m PVC Cable - 4 x wind & lux sensors - 2 x remote controls	7 x External Automated Venetian Blinds · System includes: - 35 m PVC Cable - 4 x wind & lux sensors - 2 x remote controls
Transport	25% of components imported from China / 75% of components from the UK			
Operational Energy Use				
Energy Savings provided by shading:	5 - 20 % energy savings ≡ 335 kWh/yr (10.3 mPt/yr) - 1,339 kWh/yr (41.1 mPt/yr)		5 - 20% energy savings ≡ 394 kWh/yr (12.1 mPt/yr) - 1,576 kWh/yr (48.4 mPt/yr)	
Shading Operational Energy Use:	-	· Electrical input to operate 7 x internal roller blinds, for 30 seconds, twice a day. · Electrical input to charge batteries 1.5 times per year.	· Electrical input to operate 7 x external venetian blinds, for 30 seconds, twice a day. · Electrical input to charge batteries 1.5 times per year.	· Electrical input to operate 7 x external venetian blinds, for 30 seconds, twice a day. · Electrical input to charge batteries 1.5 times per year.
End-of-Life Scenario				
Recycle:	· Fabric replaced & recycled every 5 years. · All other components reused.	· Fabric and batteries replaced & recycled every 5 years. · All other components reused.	· Batteries replaced & recycled every 5 years. · All other components reused.	· Batteries replaced & recycled every 5 years. · All other components reused.
Landfill:	· Fabric and batteries sent to landfill every 5 years. · All other components reused.	· Fabric and batteries sent to landfill every 5 yrs. · All other components reused.	· Batteries sent to landfill every 5 yrs. · All other components reused.	

***** Based on the average amount of heating energy required in a semi-detached home in the UK (DECC, 2013), **†**Based on the average modelled cooling energy required for three differing building typologies in three regions in England using DSY 2020s weather data (MHCLG, 2019c).

6.4 Results

The bar charts in Figure 141 and Figure 142 identify the embodied and operational benefit of the differing shading systems throughout their product lifetimes when considering two end-of-life scenarios: recycle and landfill. In both scenarios components that do not require replacing are reused. The embodied and operational benefit of the shading system is calculated by subtracting the embodied and operational environmental impact (in mPt) of the shading system from the operational energy saving environmental impact (in mPt). A positive value in the bar charts in Figure 141 and Figure 142 identifies a positive environmental impact, and a negative value identifies a negative environmental impact. The operational energy savings on the Y-axis in Figure 141 are based on the heating energy requirement of 6,690 kWh/yr (i.e., the heating only modelled scenario). Figure 141 presents two columns of bar charts, the left column of results relates to the shading products being sent to landfill at end-of-life and the right column to the shading products being recycled and reused at end-of-life. In Figure 142 the operational savings on the Y- axis are based on the combined heating and cooling energy requirement of 7,882 kWh/yr and the top graph relates to the landfill end-of-life scenario and the bottom graph relates to the recycle and reuse end-of-life scenario.

In all bar charts (Figure 141 and Figure 142) the 0% operational energy savings represents the operational and embodied impact of the product system only as no operational energy savings are considered (i.e., the shading system has been installed but the shading is not being used so there are no heating or cooling operational energy savings). When no operational energy savings are obtained there is a negative operational and embodied benefit (and therefore a negative environmental impact) for all shading systems. At 0% the numeric value for the operational and embodied benefit increases throughout the product systems lifetime for both end-of-life scenarios and for all shading systems. This is because during the lifetime of the product components (i.e., batteries and/or the fabric) are ‘refreshed’ and either replaced and recycled or replaced and sent to landfill. For example, at 20 years the fabric in the manual blinds has been replaced (and either sent to landfill or recycled) four times. In the case of motorised and automated systems, more electrical input is required for them to operate over the number of years they are in operation and the batteries are also replaced every five years.

When 0% energy is saved, and manual and motorised blinds are recycled at end-of-life the operational and embodied impact almost doubles between 5 - 20 years but when external automated shading is considered there is relatively little change in the operational and embodied impact between 5 - 20 years (< 5 mPt). This is because the components in external shading products are less frequently replaced as more durable materials are used in the

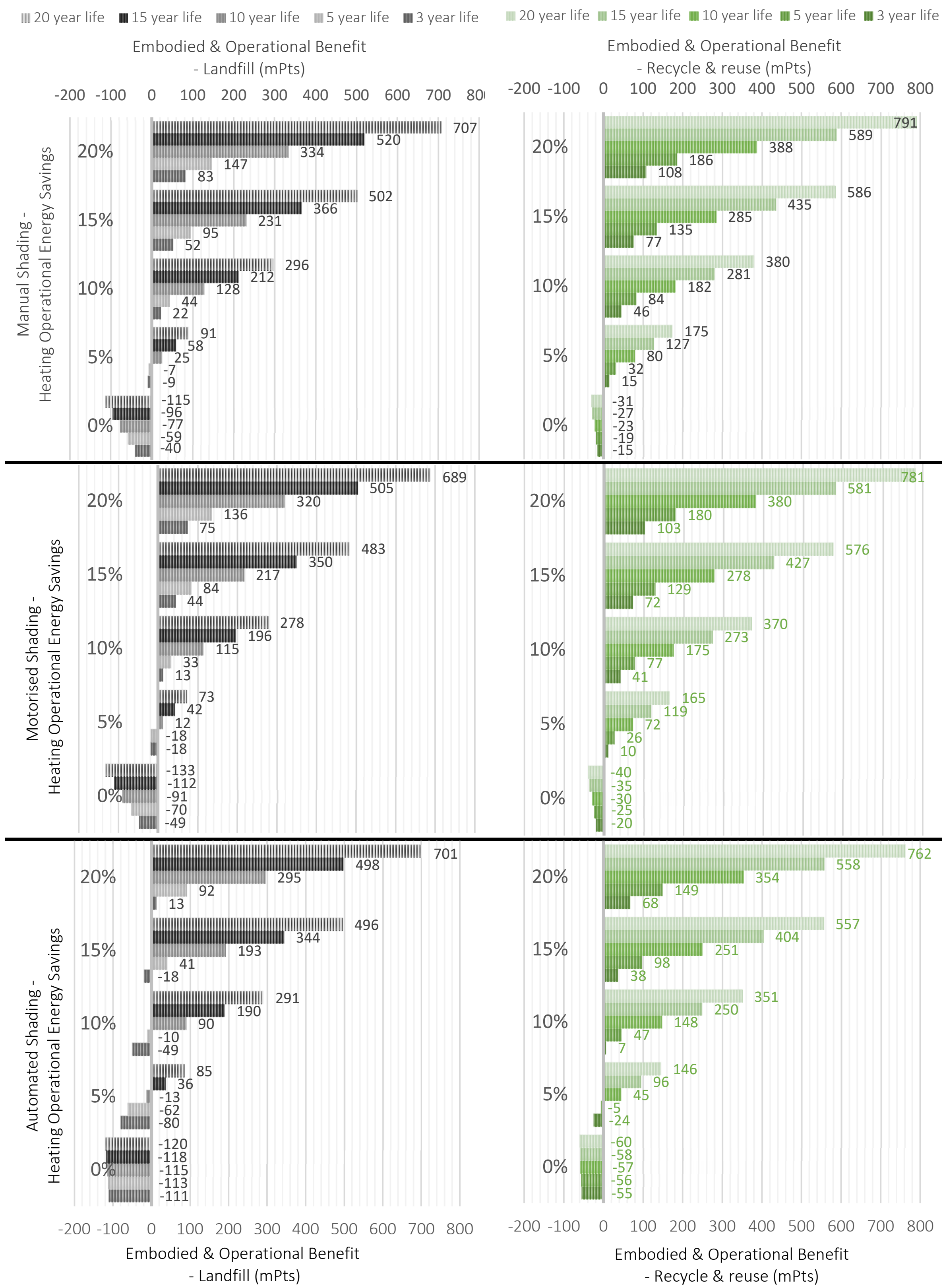

Figure 141. Operational & Embodied Impact of Manual, Motorised and Automated Shading Systems when sent to Landfill or Recycled and reused (Heating only model)

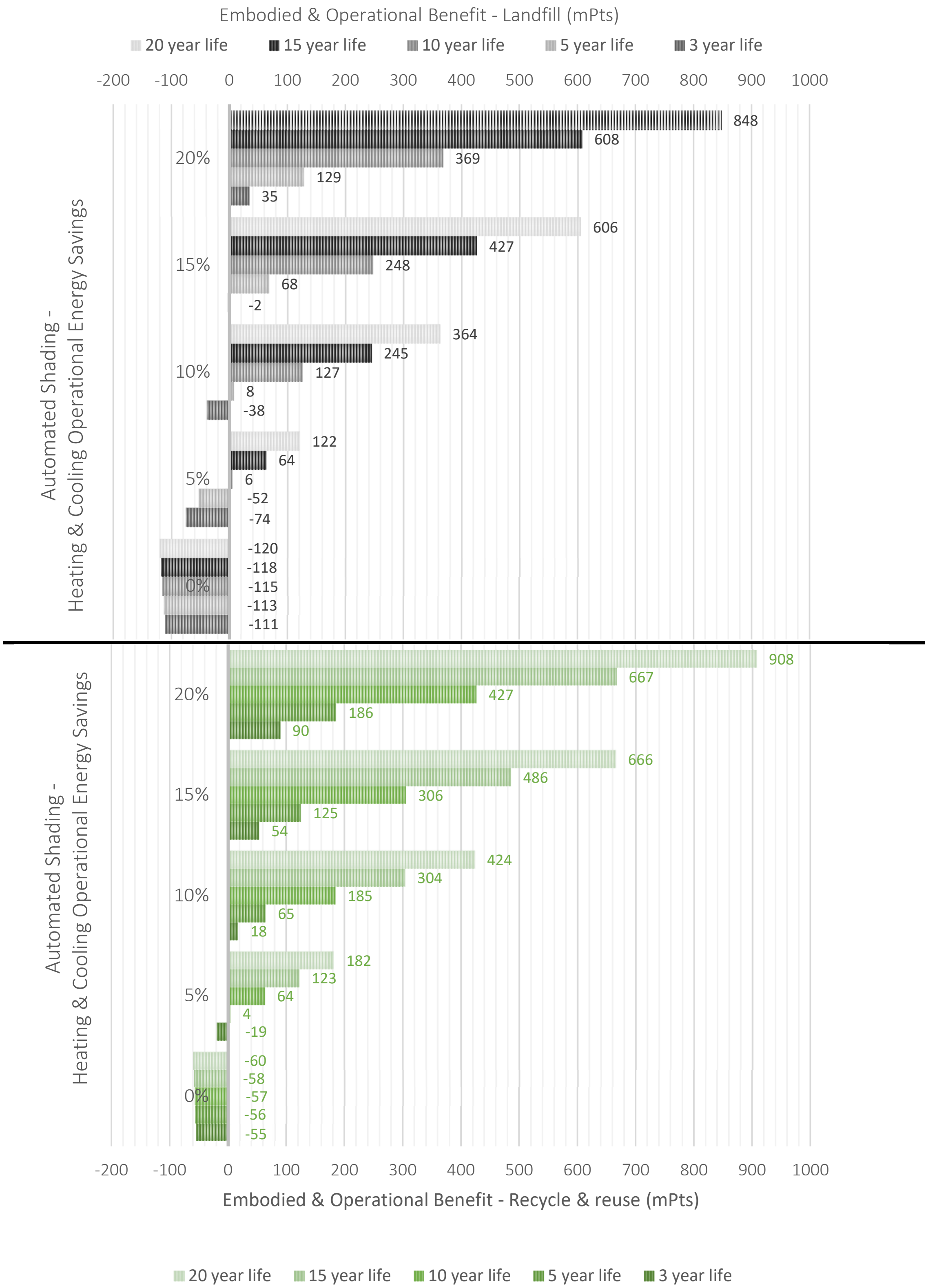

Figure 142. Operational & Embodied Impact of Manual, Motorised and Automated Shading Systems when sent to Landfill or Recycled and reused (Heating & Cooling model)

curtain of the shading product and they also are not usually replaced in the redecoration of a home. The < 5 mPt increase reflects the environmental impact of the batteries being replaced and the electrical input needed to operate them. This suggests that the energy required to operate these products has a relatively insignificant impact on the environment. When manual and motorised shading systems are sent to landfill at end-of-life the operational and embodied impact increases by almost 3 times the amount between 5 - 20 years. Like the recycled scenario there is very little increase in operational and embodied impact for the automated external shading system when it is sent to landfill at end-of-life (< 10 mPt).

When comparing the systems overall, the internal manual shading system had the highest operational and embodied benefit followed by the internal motorised system and then the external automated shading system. However, it can be observed in Figure 141 that at 20 years for all operational energy savings, the internal motorised shading system had a lower embodied and operational benefit than the external automated shading system. At 20 years the fabric and batteries in the internal motorised shading model had been replaced and sent to landfill four times where within the external automated shading model only the batteries were replaced. There were also slight differences in the amount of electrical input each of the systems required. However, the frequency of the fabric replacement in the motorised shading system was the main contributing factor to why over 20 years internal motorised systems were found to be less environmentally beneficial than the external automated shading systems when sent to landfill.

To better identify the point at which the operational and embodied benefit (operational energy savings (in mPt) less the embodied impact (in mPt) of the shading system) starts to provide an environmental benefit to the building Table 64 and Table 65 present the operational and embodied benefit as a percentage of the environmental impact of the operational energy needed to heat and/or heat and cool the building in mPt. This percentage is calculated by dividing the operational and embodied benefit by the operational environmental impact of the base case (i.e., the ‘without shading’ model). A negative percentage shows that no environmental benefit derives from blind use because the combined embodied impact of the blind and the operational energy outweighs the positive impact associated with energy savings, i.e., the benefits of blind use are below the environmental pay back point. The results for the functional unit that required heating energy only are presented in Table 64, and Table 65 presents the results for the functional unit that required both heating and cooling energy.

Table 64. Environmental Impact of Manual, Motorised and Automated Shading Systems inclusive of the operational heating energy savings.

Operational Annual Heating Energy Savings*	Control System	End-of-life Scenario	Operational and Embodied Environment Savings: Product Lifetime (Years) 3	5	10	15	20
5%	Internal Manual	Recycle	2.51%	3.13%	3.88%	4.13%	4.25%
		Landfill	-1.48%	-0.71%	1.24%	1.89%	2.21%
	Internal Motorised	Recycle	1.70%	2.53%	3.52%	3.85%	4.02%
		Landfill	-2.88%	-1.78%	0.59%	1.37%	1.77%
	External Automated	Recycle	-3.91%	-0.46%	2.21%	3.10%	3.55%
		Landfill	-12.95%	-6.00%	-0.62%	1.18%	2.08%
10%	Internal Manual	Recycle	7.51%	8.13%	8.88%	9.13%	9.25%
		Landfill	3.52%	4.29%	6.24%	6.89%	7.21%
	Internal Motorised	Recycle	6.70%	7.53%	8.52%	8.85%	9.02%
		Landfill	2.12%	3.22%	5.59%	6.37%	6.77%
	External Automated	Recycle	1.09%	4.54%	7.21%	8.10%	8.55%
		Landfill	-7.95%	-1.00%	4.38%	6.18%	7.08%
15%	Internal Manual	Recycle	12.51%	13.13%	13.88%	14.13%	14.25%
		Landfill	8.52%	9.29%	11.24%	11.89%	12.21%
	Internal Motorised	Recycle	11.70%	12.53%	13.52%	13.85%	14.02%
		Landfill	7.12%	8.22%	10.59%	11.37%	11.77%
	External Automated	Recycle	6.09%	9.54%	12.21%	13.10%	13.55%
		Landfill	-2.95%	4.00%	9.38%	11.18%	12.08%
20%	Internal Manual	Recycle	17.51%	18.13%	18.88%	19.13%	19.25%
		Landfill	13.52%	14.29%	16.24%	16.89%	17.21%
	Internal Motorised	Recycle	16.70%	17.53%	18.52%	18.85%	19.02%
		Landfill	12.12%	13.22%	15.59%	16.37%	16.77%
	External Automated	Recycle	11.09%	14.54%	17.21%	18.10%	18.55%
		Landfill	2.05%	9.00%	14.38%	16.18%	17.08%

Black (positive) figures - blind use: embodied and operational benefit is GREATER than that of not having blinds.

Red (negative) figures - blind use: embodied and operational benefit is LESS than that of not having blinds.

* Total Heating Energy = 6,690 kWh/yr ≡ 205 mPt/yr.

In Table 64 it can be observed that manual shading devices are always environmentally beneficial if recycled at end-of-life. When 5% of operational energy is saved over 3 years the environmental impact of the energy they have saved will pay-back the embodied impact of the manual shading device and provide an additional 2.5% (15.44 mPt) environmental impact saving. However, if they are sent to landfill, they will need to be used for 10 years to pay back their embodied environmental impact. If the operational energy saved with blinds is greater than 5% then the pay-back period is shorter. Table 64 identifies that at 3 years with 10%

energy savings manual shading will be environmentally beneficial and have additionally accrued 7.5% (46.25 mPt) in environmental impact savings when recycled at end-of-life or 3.5% (21.66 mPt) if sent to landfill. In all cases recycling shading products at end-of-life as opposed to sending them to landfill can significantly reduce the time it takes for shading products to become environmentally beneficial as the overall embodied and operational environment impact is significantly lower meaning, they are quicker at becoming an energy saving benefit to the building.

The impact of the motorised shading systems is slightly worse than that of manual shading products, which is reflected in the percentage values in Table 64. For example, when sent to landfill and operational savings of 5% are obtained, after 5 years the environmental impact is approximately 1% worse than manual shading systems in the same scenario. However, as motorised shading systems are more likely to be operated, as these systems encourage users to operate them, the energy saving potential of motorised shading systems is greater (Paule et al., 2015; Sutter et al., 2006) and thus in theory should provide greater operational energy savings than 5%.

The externally automated shading system needs to provide more energy savings or be installed over a longer period than manual or motorised shading systems to be considered environmentally beneficial. Considering external shading systems are less frequently replaced and the inclusion of an automated control system means that the product can be set up to optimise energy savings this is feasible (Littlefair, 2017b). The results in Table 64 show that when 5% of the heating energy is saved and the external automated shading system is recycled at end-of-life the system needs to be operational for 10 years prior to becoming environmentally beneficial. In the same scenario both manual and motorised shading products are environmentally beneficial after just 3 years. However, when the energy savings were greater e.g., 10% and the system is recycled at end-of-life then the automated external system would pay-back the operational and embodied environmental impact within 3 years. When the product was sent to landfill and only 5% operational energy was saved it would need to be in operation for 15 years to be considered environmentally viable. However, similarly if 10% energy savings are obtained then the product would be considered environmentally beneficial within 10 years, and within 5 years with 15% energy savings, and 3 years with 20% energy savings.

Table 65. Environmental Impact of the External Automated Shading System inclusive of the operational heating and cooling energy savings.

Operational Annual Heating & Cooling Energy Savings*	End-of-life Scenario	Operational and Embodied Environment Saving				
		Product Lifetime (Years)				
		3	5	10	15	20
5%	Recycle	-2.56%	0.37%	2.63%	3.39%	3.77%
	Landfill	-10.24%	-4.34%	0.23%	1.76%	2.52%
10%	Recycle	2.44%	5.37%	7.63%	8.39%	8.77%
	Landfill	-5.24%	0.66%	5.23%	6.76%	7.52%
15%	Recycle	7.44%	10.37%	12.63%	13.39%	13.77%
	Landfill	-0.24%	5.66%	10.23%	11.76%	12.52%
20%	Recycle	12.44%	15.37%	17.63%	18.39%	18.77%
	Landfill	4.76%	10.66%	15.23%	16.76%	17.52%

Black (positive) figures - blind use: embodied and operational benefit is GREATER than that of not having blinds.
Red (negative) figures - blind use: embodied and operational benefit is LESS than that of not having blinds.
*Total Heating and Cooling Energy = 7,888 kWh/yr ≡ 242 mPt/yr, 85 % Heating and 15% Cooling.

When comparing the payback times for automated external shading between the heating only model (Table 64) and the heating and cooling model (Table 65) the time it takes for the systems to become environmentally beneficial is slightly quicker when both heating and cooling energy is required. Additionally, the operational and embodied saving is slightly higher when comparing like for like scenarios. This is because the total energy demand considered is slightly higher in the heating and cooling energy model and thus a 5% energy saving in the heating and cooling model has a greater environmental impact than a 5% energy saving in the heating only model.

In the heating and cooling model when the external automated shading system is recycled at end-of-life a minimum of 5% operational energy savings needs to be obtained over 5 years for the system to be considered environmentally beneficial. When sent to landfill and 5% energy savings are obtained the system needs to be in operation for at least 10 years for the product to be considered environmentally beneficial. As mentioned previously, the larger energy savings are more obtainable with external automated shading products particularly if these systems are programmed to operate to ensure they prioritise energy efficiency. However, in residential homes they are more likely to be programmed to balance both energy efficiency and the comfort of occupants. If 10 or 15% of energy is saved, and the system is sent to landfill at end-of-life the system will be environmentally beneficial after 5 years. When recycled at end-of-life and these larger energy savings (10 and 15%) are obtained the shading system can be considered environmentally beneficial after just 3 years.

6.5 Discussion

For all systems, the operational and embodied impact of shading systems increases throughout the product lifetime in both end-of-life scenarios. The increase in the operational and embodied impact of these systems is dependent on the product lifetime, the components that are replaced throughout the products lifetime and in the case of motorised and automated shading systems the amount of electrical energy input they require to keep them operational.

When evaluating just the operational and embodied impact of the differing shading systems interestingly at 20 years the motorised shading system exceeded the operational and embodied impact of the external automated shading system when sent to landfill. External shading systems are made of heavier and significantly more robust materials and therefore generally assumed to have a greater operational and embodied impact than both manual and motorised internal shading systems. However, the 'fabric refresh' included in the internal motorised shading system model, meant that the operational and embodied impact of the internal motorised system exceeded the impact of the external automated shading system. The maintenance assumptions included a 'fabric refresh' for both manual and motorised internal shading systems. The frequency of the 'fabric refresh' was based on anecdotal evidence of how often occupants redecorate their homes. Potentially if neutral colours were chosen internal shading fabrics may not need to be replaced as frequently (or at all) when redecorating and thus the operational and embodied impact of the motorised blind would reduce. If different maintenance assumptions were included in the model, internal motorised shading products would have been more environmentally beneficial than an external automated shading system at 20 years. However, without better data on how often components are replaced and maintained it is difficult to be certain about these results.

The study results are further limited by the number of end-of-life scenarios assessed because of the lack of robust data on the length of time products are installed for and information on how products are treated at end-of-life. Even though the results of this study and other LCAs are limited to the assumptions included within them, the methodology used and presentation of results in this study allows for some of the assumptions to be explored. The use of this method helps inform manufacturers and consumers of shading products about the range in overall environmental impact of these products when considering differing operational energy savings and the lifetime of shading products. The methodology could be improved upon by integrating more accurate operational energy saving data by incorporating the outputs of building simulation tools which consider the specific design of the building and thermal properties of specific shading products more robustly. However, the inputs into building simulations should consider differing opening and closing behaviours based on actual human behaviour. It may be possible to provide a best- and worst- shading use scenario by adjusting the parameters of when shading products are opened and closed in simulations. The operational energy savings related to these inputs could then replace the minimum and maximum operational energy saving steps assumed based on research literature in this study (i.e., the 5 - 20% stepping). However, the operational energy predictions from building simulations should be verified with actual building energy performance to ensure that the building simulation outputs are representative of the real-world situation. Currently there is some concern that the impact of shading products are not accurately represented in all building simulation software systems and there are acknowledged differences in outputs when like for like simulations are carried out (Gergaud and Liaros, 2018).

Automated systems could be viewed as unfavourable to manual and motorised shading systems if only the ‘product stage’ (i.e., ‘cradle to gate’) is considered as automated systems have a higher embodied carbon requirement. However, if the ‘Product in Use’ stage and the likely end-of-life scenario (recycling due to (WEEE) legislation (Office for Product Safety and Standards, 2018)) is considered, then as long as the system is installed for 5 years and provides 5% more operational energy savings then the manual and motorised shading systems then they will be more environmentally beneficial. Similarly, internal motorised shading systems need to provide 5% more energy savings for them to be considered more environmentally beneficial than manual shading products, but the product lifetime does not need to be greater. However, this assessment is specific to the study modelled. The automated shading system used within this study was relatively basic in setup as only lux and wind sensors were incorporated within the system design. More advanced systems that collect further environmental data (e.g., solar radiation and/or air temperature data) are believed to provide greater energy savings as it is felt that these systems will better predict when blinds should open and close to save the greatest amount of energy savings. However, these more advanced systems will have a greater operational and embodied impact due to the incorporation of more sensors. Further work should investigate the impact of differing set-ups to identify if the increased complexity in componentry and manufacturing processes outweighs the environmental benefit they provide and how this effects the amount of operational energy that needs to be saved. Additionally, further LCAs should assess differing building types that explore a wider range of product types e.g., awnings, wooden venetians, vertical blinds etc. and shading systems e.g., internal, and external.

In the future air conditioning is more likely to be incorporated into the design of domestic buildings due to climate change, particularly in urban cities where external air temperatures are warmer. Air conditioning use will increase the total energy required to keep a building thermally comfortable and the refrigerants used in air conditioning units likely have a greater environmental impact than the energy required by these systems to operate. Some energy studies have found that installing and using external shading can eliminate the need for air conditioning all together (PHYSIBEL, 2005; Ylitalo et al., 2012). Further studies that compare the environmental impact of external shading systems with the environmental impact of air conditioning inclusive of the embodied impact of the cooling system itself would be a worthwhile comparison to encourage the uptake of external shading prior to air conditioning. This information would help provide a better understanding of the overall environmental impact of a building, inclusive of all building materials and products, and will enable building designers to select the optimum design strategy to produce Net Zero Carbon buildings and meet the UK energy targets.

The shading industry should work with building simulation software designers to improve how shading is represented in building models and provide guidance in how shading products should be operated in building models to reflect how shading products are operated throughout the year in real buildings. This will help improve operational energy predictions so more robust LCA's can be conducted. Additionally, the shading industry should work towards identifying how shading products are maintained throughout their lifetime, how long they are installed for and how they are treated at end-of-life.

6.6 Summary

The outcomes of this study provide the shading industry and consumers of shading products with a better understanding of how optimising the control strategies for shading products (e.g., by including motorisation or automation) impacts the overall environmental impact of the products they install and purchase. The presentation of results allows for further insights into how environmentally beneficial differing shading systems are depending on how long they are used for and how much operational energy is saved. The study identifies that it is imperative that more advanced systems (in terms of componentry and controls) are designed so they have a sufficient lifespan and/or provide a greater level of energy savings than traditional manual blinds as otherwise they could have a negative environmental impact due to the higher embodied and operational impacts of the product systems. 'Cradle to Cradle' and

‘Cradle to Grave’ LCAs will only identify the true environmental impact of shading product systems if they also consider the amount of operational energy they save in the ‘Product in Use’ stage of LCAs as well as the energy these more advanced systems consume when being operated. The study also shows that there is significant benefit to recycling and re-using components within shading systems as opposed to sending them to landfill.

CHAPTER 7. RESEARCH CONCLUSIONS AND RECOMMENDATIONS

7.1 Overview

This chapter presents the research conclusions to the aims outlined in Chapter 1 (and repeated below) with consideration to the overall research question.

"Is there a sustainable benefit to installing and using solar shading products in homes and offices in the UK?"

This chapter has been structured to highlight the research outcomes in relation to the environmental, economic, and social benefits that further support solar shading as a sustainable asset to the built environment.

The research aims were to:

Aim 1: Investigate the extent that shading products (internal and external) mitigate temperature increase in domestic buildings in the UK.

Aim 2: Evaluate how internal shading products affect occupants and their internal environments.

Aim 3: Investigate how different fabrics used in internal shading products influence the internal acoustic environment.

Aim 4: Evaluate the environmental impact of differing shading products that use different control strategies (specifically manual, motorised, and automated shading) and identify at what point the environmental benefit obtained from the operational use of the shading systems offsets the environmental impact of the product itself during its lifetime.

7.2 Environmental and Economic Benefits

7.2.1 Energy Savings through the Reduction of Overheating

Within **Chapter 3**, internal and external shading reduced the internal operative temperatures within two real-world case study buildings that are representative of UK domestic buildings. The presence of shading reduced internal operative temperature increase by between 1 and 18°C (see Table 10, p. 91 and Table 16, p. 105) which relates to a 43 - 100% reduction (see Section 3.5.2, p. 81 and Section 3.6.2, p. 97) in the number of overheating hours experienced when CIBSE TM52 Criteria 1 was used to assess the overheating risk. These results resolve **Research Aim 1** in relation to the specific buildings investigated, however the results can only be considered relevant to the case study buildings monitored and the simulated behaviours applied to the way the windows and shading systems were operated (see Section 3.2.5, p. 66 and Section 3.3.5. p. 72). To fully resolve **Research Aim 1** further systematic overheating evaluations would need to be carried out on differing building designs, in differing UK regions, with differing shading systems and assess different opening and closing strategies of shading in combination with other methods of mitigating overheating (e.g., ventilation strategies). Despite **Research Aim 1** not being fulfilled more information about the way shading products effect internal temperatures were found.

In Case Study 1 (representative of a recently renovated London apartment to Building Regulations 2010) the effect of internal and external shading combined with night-time ventilation were compared, somewhat expectedly, external shading was found to be most effective at reducing internal temperature increase. However, interestingly internal shading was able to achieve 73% of the operative temperature reduction that external shading was able to achieve in this building. This finding suggests that in similar building types (e.g., heavily glazed apartments in London) where external shading cannot be installed, internal shading (which is conventionally installed in many UK homes) can be used as an alternative to reducing the frequency and severity of overheating caused by excessive solar gains. This maybe a beneficial strategy for policy makers to consider when advising homeowners in how to retrofit the existing housing stock for climate change. However, homeowners need to be educated in how to best operate shading systems (e.g., close shading during daylight hours when internal temperatures are too warm in the cooling season and open at night to allow the building to cool more effectively).

An unexpected finding in Chapter 2, was that overheating was observed to occur in mid-season months (specifically October) as opposed to the more conventional summer months. Even though external air temperatures were significantly lower in October the London apartment

(Case Study 1) overheated. The south-west orientation of the building and the low altitude of the sun are the likely causes of this observed overheating event. This implies that for certain orientations of a building, and depending on the design and location of the building, overheating may not be just a summer issue. This suggests that overheating should be assessed across the whole year as opposed to certain months of the year for buildings that are orientated south-west and are prone to higher levels of solar gain (i.e., because they have large, glazed facades and due to their location). Interestingly, at the time of writing this thesis an annual assessment has been included within CIBSE TM59 (CIBSE, 2017) for the assessment of bedrooms at night-time which has been incorporated within the planning application process for domestic buildings in London (Greater London Authority, 2020).

The extent that internal shading products reduced internal operative temperatures in the two case study buildings assessed (Case Study 1, a London apartment) and (Case Study 2, a semi-detached house) differed significantly. This suggests that shading is more effective at reducing overheating when the main cause of increased internal temperatures is a result of excessive solar gains. The Case Study 2 building had significantly smaller glazed areas and was occupied during the time of monitoring so we cannot be certain that the way the building was being used did not contribute to the observed increases in internal temperatures. Nevertheless, the Case Study 1 building was unoccupied, so we can be certain that the reduction in the temperature increase (and overheating hours) was a direct result of the solar shading products being installed, and how they were operated and used in combination with night-time ventilation.

The wider implications of these research findings suggest that shading products can be considered an effective passive method (or semi-passive in the case of motorised and automated shading) of reducing internal temperature increase and subsequently overheating in certain building types. Considering that solar gains exacerbating overheating risk has a high probability of increasing due to climate change, it is important that passive measures of preventing internal temperatures from increasing are understood, valued, and incorporated within building design. This is because the alternative to incorporating passive measures, such as shading and natural ventilation, in reducing overheating are active measures (e.g., air conditioning). It has been suggested that by mid-2020s air conditioning could be in use in up to 34% of homes in London, England and by the mid-2050's air conditioning is predicted to be installed in 6 - 56% of homes across England (MHCLG, 2019a, 2019b). Furthermore, existing buildings that use air conditioning will require more electricity to keep their buildings suitably cool. This increase in electricity demand will have a negative environmental impact and will have broader implications on the environment because of the reliance on refrigerants within air conditioning systems. Increased energy use in homes will negatively affect the UKs plans of reaching its greenhouse gas emissions targets (100% from 1990's levels by 2050).

The finding that the incorporation and use of shading when combined with natural ventilation can reduce the number of overheating hours suggests that they can help provide more thermally comfortable internal environments. The inclusion of such passive products could help avoid or delay the installation of air conditioning by reducing increases in internal operative temperatures. Where the use of air conditioning is unavoidable, for example, in buildings where shading will not sufficiently reduce operative temperatures to comfortable levels, the combination of shading and air conditioning can help reduce the total requirement of energy consumed by air conditioning systems. Additionally, the sizing of air conditioning systems can be reduced if shading products are considered in the early design stage. Even though the results of this study were related to naturally ventilated domestic buildings, reductions in operative temperature increase provided by shading are also achievable in non-domestic buildings if solar gains contribute to the increase in cooling demand.

7.2.2 Impact of Improved Shading Control Systems

In **Chapter 2**, the existing literature regarding how shading products are used (e.g., when they are extended and retracted) suggests that innovations in user controls of shading products are of great importance to the energy saving potential of these products. Research surrounding actual use of manual shading products imply they are rarely used, where motorised systems can increase user interactions (see Section 2.6.2.4, p. 33). Unless shading products are used effectively the heating and cooling operational energy savings provided through improving the thermal efficiency of glazed areas are lost. Motorised and automated shading systems are two of these innovations. In recent years motorised shading systems have been adopted in domestic buildings, whereas automation is only typically installed in non-domestic buildings, except for a select few 'smart' homes. Motorised shading is believed to improve occupant motivations to open and close shading devices and therefore these products are associated with being able to provide greater heating and cooling operational energy savings than manual shading products. Automated systems can link to internal and external environment sensors and thus they have the potential to save further operational energy if the algorithms are set up to do so and commissioned correctly. However, occupant preference may mean these algorithms are overridden to provide more comfortable internal conditions. For example, if glare is experienced when there is low-angle sun it may mean that occupants extend shading even though it may be more beneficial in terms of energy efficiency to have the shading retracted to allow solar gain to enter the building and heat it passively (subsequently reducing the amount of heating demand needed to heat the building). Within research literature, there is very little evidence that demonstrates how these differing shading systems are used in real buildings and how their usage subsequently affects the energy required in buildings. This is because it is difficult to monitor blind movements and identify the motivations of why shading products are extended and retracted because of the numerous reasons that shading products are operated for (e.g., security, privacy, visual and thermal comfort). Additionally, in real-world buildings there are several factors that can alter the energy used in buildings (e.g., heating and cooling set points, thermal efficiency of the building envelope, internal thermal loads), so it is difficult to separate the operational energy saved that is directly related to the operation of shading products alone.

The quantity of the operational energy savings provided by shading products is important when trying to identify the overall environmental impact of a shading product as the operational energy savings will help offset the embodied environmental impact of the product itself. Motorised and automated systems require further resources and energy required in the manufacture and operation of these shading devices and thus its logical that they will have a greater embodied and operational environmental impact than manual shading products in the product stage of a LCA (i.e., cradle to gate). Additionally, within the research literature reviewed the life expectancy of shading products is uncertain because shading products are often viewed as window furnishings as opposed to a product that is integral to the design of the building. They are often replaced during the redecoration of a home or refurbishment of a non-domestic building. However, the implication of Waste Electrical and Electronic Equipment (WEEE) legislation for the shading industry means that motorised and automated shading systems are more likely to be recycled at end-of-life as opposed to being sent to landfill.

LCA are sensitive to the various assumptions and inputs used in them and because of these uncertainties within Chapter 5 a screening LCA was carried out to provide indicative results of the environmental impact of a manual, motorised, and automated shading system with the operational energy savings and life expectancy of the products stepped. This method of presenting LCA makes it possible to resolve **Research Aim 4** as it identifies the amount of operational energy, in steps, that needs to be saved over a certain period to offset the embodied and operational environmental impact of differing shading systems.

For this screening LCA the functional unit was based on a semi-detached domestic building representative of 26% of the domestic buildings in the UK and two end-of-life scenarios were evaluated; 100% recycle and reuse, and 100% landfill. Two energy usage profiles were applied to the building and evaluated, one representing UK domestic homes in 2020 where only heating energy is required (based on 6,690 kWh/yr) and a potential future scenario where heating and cooling energy maybe needed to keep homes thermally comfortable (based on 7,888 kWh/yr with 85:15 split between heating and cooling energy usage).

The results of this indicative research based on an existing domestic buildings identified that if manual and motorised shading systems are recycled at the end-of-life, they will always be environmentally beneficial as long as they are used for at least 3 years and 5% of the operational heating energy is saved. However, if they are sent to landfill, they will either need to save 5% of the operational heating energy and be used for at least 10 years or alternatively need to save a further 5% (i.e., 10%) more energy to offset their operational and embodied environmental impact within 3 years (see Table 64, p. 386).

The operational energy steps used in this study showed that motorised and manual systems need to be installed and used for the same length of time and save the same amount of operational energy to be considered environmentally beneficial. However, manual shading products were slightly more environmentally beneficial due to the slightly higher operational and embodied impact motorised shading products have because of the larger number of resources and manufacturing processes required to produce them and the additional energy needed to operate these systems. Table 64 (p. 386) shows that motorised systems are approximately 0.8% less environmentally beneficial than manual shading systems when recycled at 3 years and 5% energy is saved. However, this difference does vary depending on the length of time operational energy is saved for but at no point are motorised shading products more environmentally beneficial than manual shading systems when they are deemed to save the same amount of energy.

The automated system assessed was an external venetian blind system which included additional sensors and was more robust in design than the internal systems. The embodied and operational impact of this system was more than double the impact of the internal motorised system (Figure 141, p. 383). Therefore, the operational energy savings need to be greater or the lifetime of the product needs to be longer to offset the products environmental and embodied impact. When recycled at end-of-life and 5% of operational heating energy is saved, they will need to be operational for 10 years before becoming environmentally beneficial and when sent to landfill will need to be operational for 15 years. However, it is likely that the operational energy saving will be greater than that of manual and motorised systems as these systems can be optimised based on the external environment data they collect and operate autonomously when the building or a specific room is unoccupied. Therefore, if 15% of operational heating energy can be saved and the shading system is recycled at end-of-life they will offset their own embodied and operational environment impact within 3 years and if sent to landfill within 5 years.

The automated external shading product was also included in the functional unit where both heating and cooling energy was required keep the building thermally comfortable. This assessment found that the amount of time it took the external automated shading system to offset its own embodied and operational impact was slightly quicker (Table 65, p. 388) as the overall energy demand used in the heating and cooling model had increased and thus the energy saving steps represented a larger environmental saving.

All the shading systems examined in this study offset their own embodied and operational environment impact associated with them as long as 5% of the total thermal operational energy is saved over 15 years, even when considering that homeowners may wish to replace the fabric of internal shading systems every 5 years. They will also provide a further environmental benefit to the building if they are continued to be used and save energy. This study has shown that manual, motorised and automated systems can be environmentally beneficial however this greatly depends on the actual energy savings provided by shading products, the length of time they are in use for and how they are treated at end-of-life.

In the literature reviewed very little research was found regarding the operational energy savings provided by shading products in the UK and the literature that was found was based on modelled simulations and mostly related to commercial office spaces as opposed to domestic homes (see Chapter 2, Section 2.6.4, p. 37). It was observed in these energy studies that the energy savings are highly dependent on when shading products are opened and closed in relation to the external environment conditions. Energy studies in domestic homes are more difficult to conduct as occupant behaviour is harder to predict and there are a broader variety of reasons as to what motivates occupants to open and close shading products in domestic buildings as opposed to non-domestic buildings. The room type and the occupancy of the room vary the use of a shading products. For example, in bathrooms shading products maybe adjusted for privacy reasons at certain times of day but otherwise moved very little throughout the rest of the day, where in rooms where occupants spend a larger proportion of their time (e.g., bedrooms and living rooms) the usage profile and rationale for moving shading is very different. Large longitudinal studies as to how shading products are used in domestic and non-domestic buildings are needed to robustly inform simulation-based energy studies which can then be validated against the operational energy used in real-buildings. Real-world longitudinal energy studies are difficult to carry out as within many buildings' energy consumption is not sub-metered by room. Additionally, user behaviour studies of the way manual shading systems are operated are time consuming to carry out and although a few have been done these often centre around non-domestic buildings, or only capture data about a small number of building types and shading products. However, with innovations in motorisation and more 'smart' home technologies being integrated into homes more data about when and potentially why shading systems are extended or retracted may become available.

7.3 Social and Economic Benefits

7.3.1 Improvement to Occupant Thermal Comfort in Summer

The literature review (**Chapter 2**) identified that an improvement in thermal comfort provided by shading and the subsequent energy savings can be associated with the following socio-economic benefits related to the mitigation of overheating:

- A reduction in morbidity and ill health in occupants in the case of extreme temperature variations;
- Improvement to general health and well-being;
- Improvement in sleep quality.

These social benefits are also related to subsequent economic benefits:

- A reduction in costs to the National Health Service in the UK;
- The use of passive measures (or semi-passive measures e.g., motorised, or automated shading) will reduce the energy used for thermal cooling or warming and will subsequently benefit those in fuel poverty in society;
- Improvements in work productivity.

7.3.2 Impact of Shading on the Indoor Environment and Occupant Comfort

In **Chapter 3**, extending shading products statistically and significantly reduced internal operative temperature increase which is subsequently beneficial for occupant comfort when cooler air temperatures are preferred. However, when shading is extended it also affects other internal environment conditions that could subsequently affect occupant comfort. When shading products are closed, they attenuate daylight and diminish views out of windows which are associated with negatively affecting occupant comfort, health and wellbeing, and productivity. Often a compromise must be struck between either cooler internal temperatures and darker internal conditions with unsatisfactory views (when blinds are closed) or warmer internal temperatures, and brighter internal conditions with satisfactory views (when blinds are open). Therefore, **Chapter 4** set out to assess the effect of shading position on the internal environment and how variations in the internal environment subsequently affected occupant perceptions of the indoor environment, comfort, health, and well-being to identify whether the position of the blind can subsequently affect an occupants' actual productivity to resolve **Research Aim 2**.

7.3.2.1 Blinds Position and the Internal Environment

In both **Chapter 3** and **Chapter 4** the extension of shading products statistically and significantly affected the operative temperature ($p < 0.001$), and in **Chapter 4**, altered the internal illuminance ($p < 0.001$).

Within the two domestic case studies, the upper and lower 95% confidence intervals identified that when blinds were closed:

- Operative temperatures were 0.94 - 18°C cooler (see Table 10, p. 91 and Table 16, p. 105) than a room without a blind.

Within the non-domestic case study, the upper and lower 95% confidence intervals identified that when blinds were closed:

- Operative temperatures were between 0.79°C and 2.22°C cooler (see Table 36, p. 238);
- Illuminance levels that were between 410 and 510 lux darker (see Table 36, p. 238).

Additionally, in the non-domestic study a small (and statistically significant) difference was observed in internal air temperatures (0.19 - 0.87°C) (see Table 36, p. 238). However, this difference was negligible due to the sensitivity of the sensors.

The finding that operative temperature differed more than air temperature when comparing blind open and blind closed scenarios suggests that the position of the blinds had a greater effect on internal mean radiant temperatures as opposed to internal air temperatures. Operative temperature is affected by changes in air temperature, mean radiant temperature and air velocities; considering air velocities were controlled within the study (by keeping windows closed) and air temperatures altered by < 1°C, we can be certain that the extension of blinds affected the internal mean radiant temperatures even though they were not directly measured. This finding is logical as when blinds are extended the amount of solar radiation entering a space is limited, which will subsequently reduce the mean radiant temperature of surfaces within a building and thus alter the internal operative temperature. A by-product of solar radiation is illuminance which also explains why internal lux levels significantly differed between blind open and closed conditions.

7.3.2.2 Blind Position and Occupant Comfort, Health, Well-being and Productivity

In **Chapter 4** (Section 4.5.3, p. 186), the internal environment variable that differed because of the blind position (reported in the previous section) also significantly varied occupants' perceptions of the indoor environment, comfort, health, well-being, productivity, and their actual objective productivity[57].

Internal environment question responses identified that variations in:

- <u>Operative temperature</u> altered participants responses to the thermal comfort (Figure 66, p. 190), and the air quality questions by 1 - 2 % (Figure 67, p. 193). Responses to the visual comfort questions varied by 1% (Figure 69, p. 199).
- <u>Air temperature</u> altered participants responses to the thermal comfort questions by 3 - 17% (Figure 66, p. 190), the visual comfort questions by 9 -17% (Figure 69, p. 199), the air quality questions by 5 - 11% and the noise sensation question by 3% (Figure 67, p. 193).
- <u>Lux levels</u> altered participants responses to the thermal comfort questions by 1% (Figure 66, p. 190) and the visual comfort questions by 11 - 32% (Figure 69, p. 199).

Overall comfort and subjective productivity question responses identified that variations in:

- <u>Operative temperature and air temperature</u> altered participants responses to the overall comfort question by 1 - 6% (Figure 70, p. 203).
- <u>Lux levels, operative temperature and air temperature</u> altered participants responses to the subjective productivity questions by 1%, 1 - 6% and 15% respectively (Figure 71, p. 204).

Health and well-being question responses identified that variations in:

- <u>Operative temperature</u> altered participants responses to the health and well-being questions by 3 - 12% and air temperature varied participants responses by 1 - 6% (Figure 72 - 74, p. 207 - 211).

Lastly, performance on the work-type productivity tests and the cognitive function tests identified that variations in:

- <u>Operative temperature and air temperature</u> altered participants text typing speed by 7% and 1% respectively (Figure 75, p. 222).

[57] Air temperature has also been included in the summary of these results as air temperature has a colinear relationship with operative temperature.

- Operative temperature and air temperature altered participants performance on the cognitive function by 1 - 6% and 1 - 7% respectively (Figure 76, p. 223).

Other environment variables, specifically dBA, CO_2 levels and relative humidity, that did not significantly relate to the position of the blinds were also found to affect occupant responses to the tests and questions which may be of interest to researchers investigating the impacts of internal environment conditions on occupants. These additional relationships are reported in Section 4.5.3. (p. 186).

Overall variations in operative temperatures altered responses the most. 70% of the significant results/responses considered within this study were altered by variations in operative temperature. The health and well-being and thermal comfort questions were most consistently affected by these variations but the amount they altered them differed depending on the specific test or question evaluated.

An additional analysis was carried out which identified what internal environment variable predicted participants responses and test performance the best and whether an increase in the internal environment variable predicted a perceived positive or negative change in participants responses and performance on the tests and questionnaires. This was done by analysing the Std. β results produced from the hierarchical regressions presented in Section 4.5.3. (p. 186). Those internal environment variables that differed due to blind movement (i.e., air temperature, operative temperature, and internal illuminance) and were also the best predictor of a change in participants responses or test performance found that:

A 3°C increase in operative temperature predicted:

- Occupants perceiving less glare issues and more unsatisfactory views.
- Occupants feeling less willing to exert effort on the tasks set (i.e., they were less motivated).
- More negative symptoms associated with nineteen of the twenty-three health and well-being questions.
- A 3 WPM slower text typing speed and a 0.5 better working memory score.

A 1.6°C increase in air temperature predicted:

- A warmer thermal sensation response and 'less acceptable' thermal conditions.
- A 'more humid' and 'stuffier' air quality perceptions and a preference for more pleasant odours and fragrances.
- A noisier acoustic environment.
- A preference for brighter lighting conditions.

- Occupants’ feeling overall more uncomfortable.
- Occupants believed their productivity was being affected[58].
- More negative symptoms were associated with four of the twenty-three health and well-being questions.
- A 1 second slower response time on the number search task.

A 259 lux increase in illuminance predicted:

- Occupants perceived ‘brighter’ and more acceptable lighting conditions, perceived the questionnaire as easier to read and reported that the external view was more satisfactory.
- A 4.2% better processing accuracy score to the incongruent stimuli on the cognitive function tests.

When directly comparing the responses of the group of participants in the two interventions (blinds open vs blinds closed) statistically significant differences in the way participants responded and performed were found. The results identified that occupants in open blind rooms felt:

- Conditions were brighter and the lighting conditions were more acceptable (Figure 88 - 89, p. 243).
- There was less glare, and the visual task was easier to read (Figure 90 - 91, p. 244).
- They were more satisfied with the external view (Figure 93, p. 246).
- Their productivity was being affected[59] (Figure 94, p. 248).

It was also found that occupants perceived the conditions as statistically significantly less humid in open blind conditions. From the environment data collected it was observed that each participants mean relative humidity exposure varied by < 5% between the two room conditions. This difference in exposure would not have been detected by occupants, however perhaps this relationship was found because a limited range of relative humidities were experienced by the participants which was a limitation of the study design.

From the group comparison of results, the finding that less glare issues were experienced when the blinds were open as opposed to closed was surprising as usually glare experiences are more frequently associated with sunlight exposure (see Figure 91, p. 244). Further analysis of the data collected found that those in closed blind conditions suggested that in most cases

[58] The question used meant that it could not be determined whether their productivity was being affected positively or negatively.
[59] It was not possible to determine whether participants perceived that their productivity was being positively or negatively affected because of the question posed.

(75%) the source of the glare was the 'computer screen' and the 'internal electric lighting' (See Figure 92, p. 245). This suggests that the closure of blinds caused uneven distributions in illuminance around the visual task. When cross analysing participants perceptions of the lighting conditions with their glare responses it was observed that when glare issues were identified in closed blind conditions, they also reported the lighting conditions as being dark and when the blinds were open as being bright. This suggests that occupants' perceptions of the lighting conditions should not be used as the only indicator as to whether glare is present or is likely to be present and glare needs to be specifically investigated to identify the cause of the glare before implementing a solution e.g., shading. This also suggests that lighting designers should consider the effect of internal lighting systems in combination with shading systems to ensure that comfortable lighting conditions are available when shading products need to be extended, e.g., when glare from the sun is experienced or overheating occurs.

A test which reduced variability within the dataset (related to gender, age, desk location, individual preferences, and expectations etc.) by comparing individual participants responses with their own response in a differing intervention was conducted. This method was only achieved through the repetition of testing and the longitudinal study design which enabled occupants to be tested in both interventions (blind open and blind closed) when the external conditions were relatively similar. These results also reached significance and found that occupants in open blind conditions identified:

- The conditions felt warmer, and participants preferred cooler conditions (Table 37, p. 238).
- The air was less fresh (Table 38, p. 240).
- Conditions were brighter, and they preferred slightly brighter conditions and the lighting conditions were considered more acceptable (Table 40, p. 246).
- There was less glare, the visual task was easier to read, and they experienced less visual strain (Table 40, p. 246).
- They were more satisfied with the external view (Table 40, p. 246).
- They were more willing to exert effort on the tasks set (Table 41, p. 248).

Furthermore, the analysis found that occupants in open blind conditions:

- Typed 3% more words per minute but processing accuracy was poorer by 1% (Table 42, p. 249).

7.3.2.3 Review of Study Design

The use of a focus group provided a vital way in obtaining additional data that could not be collected through the structured tests and questionnaires given to occupants. Through the focus group it was identified that the data collected was likely weakened by variance caused by additional factors (e.g., cheating, operational issues on the tests, test fatigue, misunderstanding the tests and questions). Where possible the dataset was corrected for these issues however further improvements to the study design are needed to reduce them further. Specifically, these should concentrate on creating a more robust and shorter test battery, increasing the variations in the tests or increasing the participant population being tested.

Additional factors were mentioned that could not be corrected as they were fundamental to the study design. For example, participants identified that a lack of control over the position of the windows and blinds negatively affected their mood. It is not possible to separate this 'control' factor from the actual effect the position of the blinds had on occupants because the forced interventions are needed to identify how the position of the blinds affect people. Potentially data could be collected over a longer period without forcing participants to have the blinds open or closed and instead the actual movements of the blinds could be monitored for instance, where the blinds are positioned opened or closed. However, it is unlikely that enough comparable data would be collected (e.g., blind open and closed data collected under the same external environment conditions and similar internal environment constraints). Further suggested improvements are summarised in Section 4.5.6.4 (p. 289).

7.3.2.4 Summary

Based on the results of the case studies which were conducted within a typical UK summer the following findings were statistically significant:

When blinds were closed:

- Internal illuminance and temperatures reduced.
- Perceptions of thermal comfort and air quality improved.

When blinds were open:

- Perceptions of visual comfort improved.
- Subjective productivity was positively affected as occupants were more willing to exert effort on the tasks set.

Interestingly the measures used to identify participants objective productivity were both positively and negatively affected by the position of the blind.

Furthermore, the analysis found that occupants in open blind conditions:

- Typed 3% more words per minute but processing accuracy was poorer by 1% (Table 42, p. 249).

It was observed that there is a conflict between participants perceptions of thermal comfort, air quality and visual comfort between open and closed blind conditions, which reinforces existing literature that suggest that the extension of blinds lead to both positive and negative outcomes for occupants. Interestingly in the evaluation of how the internal environment conditions affected participants performance on the productivity tests, in some of the tests an increase in illuminance predicted a better performance and an increase in operative temperature predicted a poorer performance. However, as operative temperature was the strongest predictor it overrode the positive effect of increased illuminance.

When evaluating the full dataset collected, increases in operative temperature was the best predictor for participants reporting more negative symptoms of health and well-being. This implies that closing blinds can be beneficial for participants self-assessed health and well-being. However, to robustly prove this finding a more effective shading product would need to be installed (i.e., external shading) and the experiment repeated as there was only a small difference in operative temperatures between the blind open and blind closed conditions in the non-domestic case study. Contributing to why there was no statistically significant difference found between the way participants responded to the health and well-being questions between the conditions.

These results should be viewed with caution as a number of the outcomes of the statistical analysis were unsupported by wider research literature. The lack of consensus with prior research could be because; a very limited amount of research has been carried out where the impact of multiple internal environment variables are assessed or related to the study design and methods chosen. The limitation of this study design was that a large variation in internal objective environment conditions (i.e., temperatures, noise conditions (dBA), CO_2 levels, humidities) were not collected, and the internal conditions only really varied considerably in illuminance. There was also additional variance within the dataset because of the potential inefficiencies identified in the study design (e.g., questionnaire fatigue, practice effects, specific tests not working effectively and potential cheating on the tests), and the small data sample which considered the responses of nineteen participants over fifteen test days.

Furthermore, these results can only be associated with internal environments where internal conditions are warmer than the recommended comfort threshold and only relate to one shading system. A further longitudinal study would need to identify whether the same outcomes are found in colder conditions and whether differing shading systems affect occupants in the same way.

7.3.3 Shading Fabrics and their effect on Acoustics

Chapter 5 identifies a way of including the acoustic absorption properties of shading fabrics within early design acoustic assessments to help determine the reverberation time of a room. It also identifies both the sound insulation performance and the acoustic absorption of shading fabrics used typically in UK buildings to help answer **Research Aim 3**. Evaluating the acoustic design of a building by identifying how furnishings will affect an occupant's experience of the internal environment can be beneficial in improving occupant comfort. Prior literature identifies that acoustic discomfort is problematic in both residential and commercial buildings due to the transmission of noise into the indoor environment and reverberation of sound within the indoor spaces. Reducing dissatisfaction with the acoustic conditions in office spaces is believed to reduce stress and improve the overall well-being of occupants. This can also be related to improvements in productivity and although this has not been conclusively identified within this thesis it is supported in the literature reviewed.

7.3.3.1 Transmission of Sound and Shading Fabrics

Acoustic discomfort due to the transmission of sound is likely to become an increasing problem in residential homes because of the reliance on natural ventilation to cool the indoor environments and because of the increase in population in urban areas. Shading devices are frequently extended to reduce internal luminance levels at night in bedrooms and are therefore more likely to be the only barrier against external noise when windows are opened. However, due to the variety of shading fabrics supplied by manufacturers and the lack of an inexpensive and reliable method in testing differing shading fabrics in Europe these benefits are overlooked.

An international standard (ASTM) testing methodology was used and adapted to identify the transmissive properties of various shading fabrics. Traditionally this standard is used to identify the acoustic properties of other building materials e.g., insulation material. Difficulties were experienced when carrying out testing because of the lack of information of how to position fabrics and the inability in testing structured shading fabrics, which would likely cause variation between data when comparing fabric products. Nevertheless, these barriers were overcome although the number of samples tested was reduced.

The work carried out identified that:

- Some shading fabrics commonly used in roller blinds provide an acoustic benefit when weighted against external noise traffic and living activity noise.
- Two of the five fabrics provided a reduction of R_w 5 (-0; -1) dB and R_w 10 (-1; -2) dB, which is perceptible by occupants (see Table 62, p. 361) where three of the five fabrics had a $R_w < 3$dB, which is imperceptible to occupants.
- Shading fabrics are more effective at reducing medium and higher frequencies of sound similar to acoustic absorbers.

Whilst these values identify the acoustic properties of the shading fabrics, further testing is needed to test how these fabrics perform when used in a free hanging roller blind system, a zipped system and other alternative shading systems. This testing should also consider the air gaps between the glazed surface and the fabric as this difference could also vary shading system performance. BS EN 10140 (BSI, 2016) should be used as a basis for this further testing.

7.3.3.2 Absorption of Sound and Shading Fabrics

Testing method BS EN ISO 354 (BSI, 2003) and classification method BS EN ISO 11654 (BSI, 1997) was used to compare differing shading fabrics and their acoustic absorption performance:

The work carried out identified the that:

- The performance of shading fabrics varied the weighted absorbency coefficient between a α_w 0.55 (M/H) which is equivalent to an ISO Class D absorber and a α_w 0.00 which is equivalent to a non-classified absorber (Table 59, p. 343).
- The installation distance of shading fabrics can impact the overall α_w and related α_{pi}.
- Generally increasing the distance between the fabric and the room surface improved the absorptive properties of the shading fabric, however certain frequencies of sound were affected more than others. Testing can help identify an optimum installation distance for certain frequencies of sound.

When including the absorptive properties of shading devices within a theoretical early design assessment of an office, with 5.65m^2 of glazing with a window to wall ratio of 12%, the predicted reverberation time reduced by 0.07 seconds (Table 60 - 61, p. 357). This contribution to the reduction in acoustic reverberation, although small, can still be considered a benefit when rooms are found to be too reverberant and detrimental to acoustic comfort. However, there is little guidance as to what the most appropriate reverberation requirement should be for specific rooms except for the guidance provided for different room types within schools where new offices should aim to achieve a reverberation time of 1 second (DfE, 2015).

However, as the shading fabrics were only tested when they were extended further work should be carried out to identify the effect of shading fabrics when they are fully or partially retracted. It is expected that this will diminish the absorptive properties of the shading product as the surface area will be significantly reduced which will place a further limitation on how practical shading products are at reducing reverberant sound. Additionally, the absorptive benefit of shading products in differing building types or room types may identify where the integration of shading fabrics can be most useful. For example, in glazed foyers and conservatories they may be very beneficial because of the large area of hard reflective surfaces. Comparisons of performance should also be made with similar product types (e.g., acoustic curtains, wall hangings) and other room furnishings (e.g., carpets, ceiling tiles and furniture) to identify their true benefit within building design.

7.4 Recommendations for Future Research and Industry

<u>Designing buildings to reduce Overheating.</u>

Industry should consider evaluating the design of buildings for overheating risk in months other than summer, and future climate scenarios should be evaluated so buildings can be designed to avoid (or minimise) the need to incorporate air conditioning. At the time of writing an annual assessment of the number of overheating hours in bedrooms (CIBSE TM59) has been included within The Greater London Plan (2020).

Further research is needed to identify how the effects of different overheating mitigation methods and combinations of these methods affect buildings. This will be important when considering ways of retrofitting the existing housing stock for climate change. A standardised approach to evaluating overheating in real buildings is needed so research findings can be easily compared. Potentially this could guide researchers in the data that has to be collected, methods that should be used to collect and analyse data and the equipment to use. Real-world research is imperative to ensure prediction models of how differing mitigation methods affect buildings are validated.

Where shading products are integrated in buildings as a way of mitigating overheating and reducing internal temperatures building users need to be informed of how and when best to use them, and potentially how to use them in combination with other overheating mitigation methods (e.g., natural, and night-time ventilation). This guidance needs to be kept simple for building owners to understand and pass on to occupants.

Longitudinal Energy Studies and User Behaviour Studies

Longitudinal energy studies that are informed by user behaviour studies of how people use shading products in real buildings are needed to provide better information on how shading products affect the energy consumption of buildings, their overall environmental impact and allow for better predictions of how the internal environment conditions will vary when shading products are operated. Currently building simulation studies set when shading products should extend and retract based on the thermal conditions (e.g., vertical solar radiation levels at the window or internal/external temperatures) however, in observational studies carried out in real buildings it is found that occupants open and close shading products for a variety of reasons (e.g., security, privacy, visual and thermal comfort). A better understanding of occupant behaviours could lead to better assumptions being included in building simulations to better predict the impact that shading products have on the energy consumption of buildings.

Furthering research in the way Shading Products affect Occupants.

The trade-off between improved visual comfort and thermal comfort should be explored further to identify a threshold where poor thermal comfort outweighs the benefits of good visual comfort. Advances in wearable technologies, Building Management Systems (BMS), and Smart Homes may mean that both data related to occupants and the indoor environment becomes more obtainable. The inclusion of blind movements in BMS could help better identify the effects of the internal environment on occupants inclusive of blind use.

Acoustic potential of Shading Products

Fabric manufacturers should develop a standardised test method for testing the transmission and absorptive properties of shading fabrics so the properties of fabrics alone can be evaluated and benchmarked against one another for the purpose of selecting shading fabrics. For absorption testing the standard can be based upon BS EN ISO 354 (BSI, 2003). For transmission testing potentially an adaptation of the ASTM E2611- 17 (ASTM International, 2017) would be suitable for structurally flat fabrics. The shading industry should develop a more detailed method of assessment that should define methods of testing different shading systems that detail the distance that shading fabrics should be installed from the window which would provide an indication of the acoustic performance when installed in a building.

The real-world impact of the absorptive acoustic and the acoustic insulation properties of shading fabrics needs to be further considered by evaluating how the installation of shading fabrics will alter the reverberation time within a room and the overall sound level in different room sizes, with different sized glazed areas and with different furnishings included within the room.

7.5 Original Contribution to Knowledge

This thesis contributes to literature on how installing and using shading products provide a sustainable benefit in homes and offices in the UK by:

- Applying statistical techniques and existing UK industry methods for evaluating overheating risk to identify the extent that internal and external shading products effect internal temperature increase in two case study buildings representative of domestic buildings in the UK.
- Undertaking a qualitative and quantitative analysis of the impact shading products have on the internal objective environment and occupant perceptions of the internal environment, their own comfort, health and well-being, subjective productivity, and objective productivity.
- Outlining a way of theoretically calculating the impact internal shading fabrics can have on reverberation times within an office.
- Applied an existing method of evaluating the sound insulation properties of building materials to conventional shading fabrics used in UK buildings.
- Produced a way of presenting the environmental impact of differing shading products that allows for easy comparisons between differing shading products and carried out a component level embodied environmental impact assessment of manual and motorised roller blinds and an automated external venetian shading system.

7.6 Summary

Lastly, whilst the research undertaken has highlighted several benefits that suggest shading products can be a sustainable asset in UK buildings, if they are not effectively and efficiently operated the benefits they offer will be diminished.

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