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Recognising the cognitive functions involved in productivity loss associated with temperature changes

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SUMMARY
A poor indoor environment can detrimentally impact occupants' health, wellbeing and productivity. Indoor temperature is an important and easily controlled parameter of indoor environment quality and might affect productivity. Productivity is a general term that describes the ability to perform tasks, relying on cognitive systems such as executive function, memory and attention. Research to date has tended to view 'productivity' as a single construct and has not asked whether the various mental components underpinning productivity are affected differently by realistic changes in the environment. In this study, 54 participants undertook a range of cognitive tests – each tapping different underlying cognitive abilities – within an environmental chamber under different temperatures. It is shown that working memory and certain executive function tasks are the most affected functions of productivity and indicate a clear optimum range of 17˚C to 25˚ C (in UK climate); tasks such as visual search showed no effect of temperature. However, the effects of environmental conditions were smaller than the differences between individual participants that were observed. This important inter-person variation notwithstanding, understanding the impact of temperature on cognitive functions will impact both productivity and energy use within offices. Significantly, this has environmental and financial implications on building operation and staff productivity.

KEYWORDS
Thermal comfort, Indoor Air quality, productivity, Work performance, Cognitive functions

1 INTRODUCTION

People spend 90% of their time in indoor environments including office spaces and, therefore, office indoor environment quality (IEQ) plays an important role in occupants' health, wellbeing and productivity. Given that the main proportion of companies' costs are allocated to staff salaries (Bluyssen, 2014, Lan and Lian, 2009, Wyon and Wargocki, 2006) , productivity could be a significant motivator for designing the office buildings' indoor environment. Temperature is an important parameter of IEQ and can significantly affect productivity. Two main theories consider this relationship: the inverted-U theory and the extended-U theory. These models predict the productivity under mild thermal stress which could be few degrees above or below an optimum temperature (Zhang et al., 2019). The Inverted-U theory implies that there is a well-defined optimum temperature and even few degrees variation can cause productivity loss. The extended-U theory, however, allows for individual adaptability as a physiological and psychological response of people (Hancock, 1989) and suggests that within a thermal comfort range productivity is not affected significantly and only starts to decline when the temperature is above or below this range (Hancock and Ganey, 2003, Zhang et al., 2019). Different measurement methods have been recognised as one of the possible reasons that could lead to different results (Porras-Salazar et al., 2021). Building design policies have mainly focused on reduction of energy consumption rather than occupants' wellbeing and productivity. This can define a range for temperature which does not necessarily comply with the accepted range for productivity. It is important to find a balance between energy consumption and productivity. To achieve this balance, the first aim should be to find the optimum range of temperature for productivity and then compare it with the one suggested by energy policies.

Productivity is a general term that involves various cognitive functions that are the ability and skills of the brain to perform any kind of task (Committee on Psychological Testing, 2015). These include executive function (the ability to control and coordinate other cognitive functions to facilitate achieving the goals (Miller et al., 2009)), memory and attention (Occupational Information Development Advisory Panel, 2009). The use of cognitive functions to measure productivity is common and it is considered to be one of the main indicators of individual productivity (Higgins et al., 2007, Schmidt, 2002). However, the main cognitive functions involved in office jobs are memory, attention, and executive function (Deligkaris et al., 2014). The importance of these various cognitive functions will vary depending on the nature of the tasks which are typically defined by the work environment. Some cognitive functions appear to have separate mechanisms to others, rather than all cognitive performance reflecting a single underlying ability (people can be differently skilled at different tasks, and brain injury can impair some skills while leaving others intact). As such, it is plausible that environment quality, including temperature variation, will affect some skills more than others. The aim of this paper is to assess how different cognitive functions vary with changing temperature. Cognitive performance measurement will help identify which particular cognitive functions and which specific mental mechanisms of productivity are affected by temperature.

2 METHODS

Different aspects of productivity were assessed through cognitive performance assessment under laboratory controlled environmental conditions. The VSimulator facility in University of Bath is a 3m by 4m by 3m high environmental chamber with virtual reality that can be used to simulate the required indoor environment based on the given characteristics of the room like the building height and time of the day. The VSimulator can simulate the air temperature and radiant temperature between 15 °C and 40 °C, relative humidity between 20% and 80%, airflow between 0.05 m/s and 1.5 m/s, and fresh air between 1 l/s/p and 10 l/s/p. It has capacity for up to four participants to be tested simultaneously. However according to the pilot testing of CO_2 levels, and the COVID restrictions in place at the time of the experiments, only two people have been tested simultaneously in each session.

The temperatures for the test were chosen based on the adaptive thermal comfort model. Based on the data from Met Office, the UK mean outdoor temperature in this study has been considered 10 °C (Met Office, 2020). According to adaptive thermal comfort model, while the mean outdoor temperature is 10 °C, the 80% of acceptability for occupants can be achieved between 17.5 °C and 24.4 °C. The midpoint of this range is 20.95 °C. As a result, 21 °C has been chosen as a base temperature for this study. Temperatures of 21°C ± 4 K and 21°C ± 6 K (15 °C, 17 °C, 21 °C, 25 °C and 27 °C) have been considered, having measurements both within and outside of the 80% adaptive comfort range. To investigate if there are any interactions between temperature and relative humidity, three levels of relative humidity: 30%, 50% and 70% have also been tested. These three levels are considered as low, medium and high relative humidity based on the categories suggested by Vellei et al. (2017). There are other physical parameters such as clothing level, air velocity and activity level that the thermal exposure depends on them in addition to temperature and relative humidity (Parkinson and De Dear, 2020). However, in this study these three has been kept constant. The activity level was between 1 to 1.1 MET and the clothing level was between 0.5 and 1 CLO. Environmental conditions in different test sessions of the experiment inside the VSimulator are presented in Table 1.

Table 1. Different Hygrothermal conditions experienced by each group

Group	Tested conditions (Temperature (℃), Relative humidity (%))
1	(17,30), (17,50), (17,70), (21,30), (21,50), (21,70), (25,30), (25,50), (25,70)
2	(15,30), (21,50), (27,30), (27,70)

Participants were divided in two groups: the first group of participants were exposed to temperatures 17 ℃, 21 ℃ and 25 ℃ with three levels of relative humidity (30%, 50% and 70%), the second group were exposed to more extreme temperatures: 15 ℃ and 27 ℃ and high and low relative humidity levels. Also, both groups experienced the base condition of T = 21 ℃ and RH = 50%, making comparison easier. The condition 15℃ and 70% relative humidity was not considered due to technical limitations of the test facility. The order of test conditions was randomised and unknown to the participant.

To measure people's productivity in different hygrothermal conditions, participants were asked to undertake several cognitive tests. Adaptation time was investigated, and 15 to 30 minutes was determined to be adequate. However due to limitations in this study, after entering the chamber, 15 minutes was allowed as an adaptation time to the existing condition before starting the tests. The VSimulator Test Battery (VSTB) has been designed and implemented in PsychoPy 2020.3.1 by the research team in university of Bath. PsychoPy is an open-source application using Python codes which allow researchers to design psychological tests in a GUI (Graphical User Interface) environment. In this study, PsychoPy 3.1.5 has been used as a platform to perform simulated office tasks and cognitive tasks. The battery consists of six cognitive tests and two additional office simulated tasks. The cognitive functions tested in the VSTB includes:

1) Attention
    a) Rapid Visual Information Processing (RVIP): In this test a sequence of one-digit numbers is displayed in a random order. Participants are asked to look for a particular sequence including three consecutive digits (e.g 3,5,7) and press "space" whenever they detect it. This test is a measure of sustained attention.
    b) Visual Search: In this test a hexagon is displayed among eight pentagons (the distracters) and the participant must identify and select the hexagon as quickly as possible within 5 seconds. The reaction time is measured in this test. The visual search test is to measure the visual attention.
2) Memory
    a) Corsi: This test is a measure of visual working memory. In each trial five squares are shown to participant in a sequence. The participant needs to remember the sequence and click on squares to repeat it in the same order.
    b) Letter span memory: In this test ten random letters are shown on the screen in random positions for 5 seconds. the participants are asked to read the letters out loud. Then the letters disappear, and a target letter appears on the screen. The participant must identify if this letter was there or not. This test is to measure the verbal working memory.
3) Executive function
    a) Stroop: The Stroop Colour and Word Test (SCWT) is a neuro-psychological test that can measure the ability to inhibit cognitive interference or executive function. On the screen, a stream of single words is displayed at the rate of 60 word per minute. The word is a name of a colour (blue, red, green) and it is shown in a colour sometimes congruent

with the word and sometimes not. So, there are two interfering stimuli; one is the ink colour that the word is shown in and the other is the word itself, which is a name of a colour (blue, red, green). The participant should ignore the word itself and should focus only on the ink colour of the word and press an associated related key on the keyboard as quickly as possible. Because of the conflict between the desire to read the word and to name the colour of the word, the participants executive function is being tested during this test (Gilbert and Burgess, 2008). This test has been also used to measure attention, cognitive flexibility, processing speed and working memory.

   b) Go/No go: This test measures the inhibition ability of participants. So, when they see a green "Go" on screen they should press a key within 1.5 seconds and when they see a red "No Go" they must not press any key. There are more "Go"s than "No Go" s providing an expectation which makes this test more difficult. This test is a measure of executive function.

Three office simulated tasks have also been included in the test battery to represent office tasks in a more realistic way.

4) Office Simulated tasks
   a) Addition: In this task, participants add two numbers of two digits each as quickly as possible. The numbers are selected randomly. Accuracy and reaction time are recorded.
   b) Typing: In this test, a paragraph of about 400-500 word appears on screen and participants must type the text as quickly and as accurate as they can. There are several randomly selected texts, each text having been selected to be similar in length and difficulty. The accuracy of the typed text and the speed (words per minute) is calculated.

The order of testing might be an issue if later tasks are helped by practice or hindered by fatigue (Tao et al., 2019). Two solutions were used to remove possible learning effects. First, one week before the experiment, people have been sent a 15-minute video explaining how to complete each task; second, to counterbalance the impact of learning, the order of conditions was changed randomly so there was no pattern to which tasks were tested in which order.

3 RESULTS AND DISCUSSION

A total of 54 subjects (25 male and 29 female volunteers), between ages 19 to 50 years old, participated in this experiment. In each test, productivity was measured in terms of accuracy and reaction time, except in visual search in which only reaction time has been considered. The ratio of reaction time to accuracy has been calculated as the "Effort score". The higher the effort score, the lower the performance (a high score might therefore reflect long reaction times and/or a small number of correct responses). For calculations, all accuracies and reaction times have been standardised as Z-scores to enable scores from multiple tests to be combined and compared. For each category of tests, the effort score has been calculated by averaging the effort scores of the tests in that category. The results are illustrated in Figure 1, where the data has been normalised against the base condition of 21 ℃ and 50% RH. Figure 1 clearly shows that the productivity within the 80% comfort level of adaptive thermal comfort (17 ℃ to 25 ℃) is not affected significantly (less than 9%) but moving towards more extreme temperatures of 15 ℃ and 27 ℃ in relative humidity of 30% and 70%, many of the effort scores increase significantly as high as 19% (apart from office-simulated tasks) suggesting that some aspects of productivity are impaired by these more extreme conditions.

A mixed-effect model technique has been used to analyse the data. This is preferable to Repeated-Measures ANOVA as it makes fewer assumptions about the data, can cover missing data more effective, and provides a useful measure of variation between people. This method also does not need fully balanced designs (Magezi, 2015), which is important as each participant in this study was not tested in all conditions. Another advantage of this model is that it can consider the interaction impact of the independent variables, temperature and relative humidity. Considering the limited number of levels of these independent variables, and that all participants have one condition in common (T = 21 ℃ and RH = 50%), temperature and relative humidity have been treated as categorical variables. The response variables in this research are effort scores from each cognitive test. The fixed variables, which are the variables that are expected to have a systematic impact on the relevant response variable, are temperature and relative humidity. Condition order, and participant ID, were added as random effects. On occasions where a participant reported that they had not understood a specific test, that person's data were removed from that individual test. The presumptions of homogeneity of variances of the residuals across groups for each random effect variable and the normality of residuals have been checked and satisfied.

In the fitted linear mixed effect model, all conditions are compared to the base condition (T=21℃, RH= 50%). P-values have been used to assess the level of significance of the impacts and in this study, a p-value lower than .05 has been considered as statistically significant. Effort score changes within the 17 ℃ to 25 ℃ range are very low and are not statistically significant in any of the functions; maximum change in this range is 0.23 standard deviations – a magnitude that would be considered small within the behavioural sciences (Cohen, 1988). However, moving towards extremes, the increases in effort scores are significant and as high as 0.47 standard deviations in Executive function (p-value = .023), 0.70 standard deviations in Memory (p-value < .001), and 0.35 standard deviations in Office-simulated tasks (p-value = .008). Not all cognitive tests were affected, however. For Attention, the changes are not statistically significant: the highest change occurred at 15℃ and is a non-significant change of 0.18 standard deviations (p-value = .419). Comparing the results due to relative humidity of 30% and 70% with the base condition (RH=50%), the changes are not statistically significant, ranging between 0.03 standard deviations decrease (Memory) to 0.18 standard deviations increase (Attention). The Interaction effect of temperature and relative humidity has been considered wherever there exist the combination data and the result shows that the interaction effect is not statistically significant and is less than 0.3 for Attention tests and less than 0.2 standard deviations for the rest.

The model confirms that the variance of random intercept within order of the tests (τ00 Order) is less than 0.04 indicating that there is no learning effect for the tests. This implies that efforts to reduce order effects through experimental design were successful. On the other hand, the variance of random intercept for participants (τ00 Participant), which accounts for individual differences between participants, is considerable in all categories: 0.53 for Executive function, 0.67 for Memory, 0.50 for Attention and 0.76 for Office-simulated tasks. This clearly shows that individual differences between people account for a more substantial proportion of variance in effort scores than the effects of temperature and RH. Marginal R^2 demonstrates that 6.5% of the variance in Executive function effort scores, 9.7% in Memory effort score, 1.3% in Attention effort score and 1.9% in Office simulated effort score are due to the fixed effects where the models can account for 61%, 69%, 50% and 84% of the variance in data set respectively (Conditional R^2). It is therefore clear that individual differences between participants account for a more substantial proportion of variance in Effort scores than the effects of temperature and relative humidity.

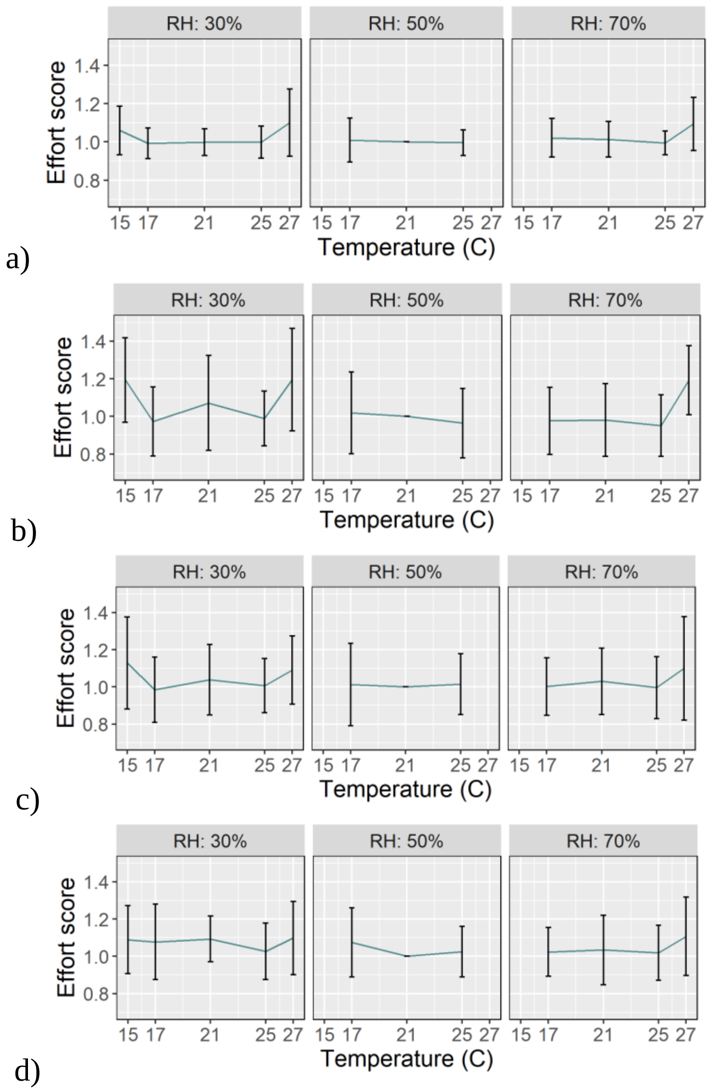

Figure 1. Normalised Effort score changes in tested temperatures and RH levels in each cognitive function. a) Executive function, b) Memory, c) Attention, d) Office simulated tasks. Error bars show the mean ± SD.

It was predicted that not all cognitive tasks would be equally affected by environmental conditions. To assess this idea, hierarchical agglomerative clustering analysis was used to perform a bottom-up search for task subgroups that showed different magnitudes of effect from temperature and RH. The marginal R^2 for each cognitive function category has been used as a measure of sensitivity to temperature. Subsets in the data were identified by looking for tests with similar marginal R^2 scores. The resulting dendrogram plot for each cognitive test is illustrated in Figure 2. The optimal number of clusters (K) has been calculated using the optimal univariate clustering function in R. The result from clustering analysis is summarised in Table 2. Based on the marginal R^2 of effort score model as a measure of the impact of temperature, four categories have been identified: Stroop and Letter-span memory tests showed large effects of temperature; there was a medium effect for Corsi and RVIP tests; a small effect for Addition and Go/No go tests, and almost no effect for Typing and visual search tests. For cognitive function categories, two clusters have been identified: the two main functions that are affected by temperature are Executive function and memory and the two which are less affected are Attention and Office-simulated tasks.

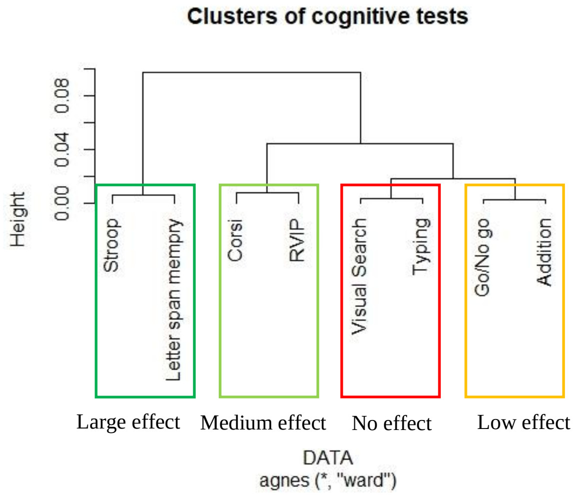

Figure 2. Cluster dendrograms for cognitive tests, Method used: Hierarchical agglomerative clustering analysis (AGNES), Ward method. The hight on vertical axis shows the similarity between objects, the higher the fusion, the less the similarity.

Table 2. Cluster analysis for the tests.

Cognitive functions	Tests	Marginal R^2 For tests	Marginal R^2 for functions	Cluster
Executive function	Stroop	0.075	0.065	Large effect
	Go/ No go	0.020		Low effect
Memory	Letter span memory	0.081	0.097	Large effect
	Corsi	0.044		Medium effect
Attention	RVIP	0.036	0.013	Medium effect
	Visual search	0.008		No effect
Office simulated	Addition	0.018	0.019	Low effect
	Typing	0.005		No effect

5 CONCLUSIONS

The impact of indoor environmental quality (IEQ) on productivity can be measured objectively using cognitive performance tests. Not all tests are affected equally by changes in IEQ, suggesting the effect on people is likely not just a global impact on, say, attention; the sensitivity level of cognitive functions to temperature is key to appreciating the broader impact on productivity and could help optimize the process of examining productivity in experimental settings. This study found four main categories of cognitive test, with some more affected by thermal than others. Based on these, the cognitive/work tests of this study have been categorized into four groups ranging from large effect to no effect from temperature. Certain executive function and memory tests appear to be the two cognitive categories most affected by temperature, while attention and office simulated tasks have lower sensitivity. It is surprising that the two tests of executive function – Stroop task and the Go/No-go task – showed different results, and this might help future work pin down the locus of any effect. Across the tests, there is a clear picture that performance is not much affected between 17 ℃ to 25 ℃ but that productivity is much more affected at 15 ℃ and 27 ℃ - a finding potentially useful for office managers. The differential pattern across the tests further suggests that future studies on temperature impact can use a subset of the cognitive tests considered here, focused particularly on functions such as executive function and memory tests which showed more sensitivity towards temperature changes.

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