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Evaluation of comfort conditions in airport terminal buildings

Alkis Kotopouleas*, Marialena Nikolopoulou

Centre for Architecture and Sustainable Environment (CASE)
Kent School of Architecture, University of Kent, Canterbury, CT2 7NZ
*A.G.Kotopouleas@kent.ac.uk

Abstract

This paper presents findings from extensive field surveys in three airport terminal buildings in the UK, where the indoor environmental conditions were seasonally monitored and simultaneous structured interviews were conducted with 3087 terminal users. Moving beyond the recent work which brought to light the significantly differentiated requirements for thermal comfort between passengers and staff, this paper expands on the investigation of thermal and lighting comfort needs for the entire spectrum of terminal users under the scope of energy conservation. The results demonstrate the influence of the thermal environment on overall comfort and reveal consistent discrepancies, up to 2.1 °C, between preferred and experienced thermal conditions. Outdoor temperature dictated the clothing levels worn indoors, where the preferred thermal state was other than neutral. Terminal users demonstrated high levels of thermal tolerance and wide acceptability temperature ranges, averaging 6.1 °C in summer and 6.7 °C in winter, which allow for heating energy savings through the fine-tuning of indoor temperature set-points. Lighting comprises an additional field for energy savings through the maximisation of natural light. Bright rather than dim conditions were preferred and a preference for more natural light was evident even in cases where this was deemed to be sufficient, while the preference for more daylight was found to be time-dependent suggesting a link with the human circadian rhythm. The findings from this study can inform strategies aimed at reducing energy use in airport terminals without compromising comfort conditions as well as the design and refurbishment of new and existing terminals respectively.

Keywords: airport terminal, thermal comfort, comfort zone, lighting, daylight, energy conservation

1. Introduction

Airport terminals are characterised by open and large spaces with non-uniform heat gains and often with extensive glazing areas aimed at providing natural light and aesthetically attractive facilities. Terminals comprise a particular type of building also from an operational perspective; accommodating a range of stakeholders and activities, terminals experience diverse and transient occupancy and long operational hours which in large airports can reach 24/7 all year round. Times of very low occupancy and times of peak occupancy can alternate several times a day while being also weather-dependent. As a result, HVAC systems use large amounts of energy that can be greater than 40% of the total electrical energy, with most of that being used by air conditioning systems, while with the exception of small systems (e.g. hot water) HVAC systems can also account for nearly all gas use at an airport [1].

While HVAC systems are most often among the highest energy end use together with lighting, outdoor temperature and daylighting are the main external influencers of energy demand patterns [2]. Reduction of the energy used for the regulation of the indoor thermal environment can be accomplished and maximised alongside other energy efficiency strategies through the optimisation of environmental controls, including adjustments of the indoor climatic set-points and of the respective heating and cooling dead bands in accordance to the outdoor weather conditions. The adoption of a broader range of indoor temperatures would yield less energy for heating, cooling and ventilation, but requires awareness and understanding of occupant comfort requirements to avoid jeopardising comfort.

Lighting also comprises a significant component for energy conservation in terminals. Beyond its general purpose in the indoor environment - of enabling occupant to work and move in safety, to perform tasks correctly and at an appropriate pace and of providing a pleasing appearance [3] - terminal lighting is also part of the establishment of character in the different areas of the building. Nowadays, airport design is increasingly making use of daylighting to improve the ambiance of the terminals and reduce lighting costs. Typical buildings that take advantage of daylight can save 40-60% of the energy used for lighting [4]. As the sunlight produces less heat per lumen of light than most electrical lighting, indirect daylighting may impose less demand on the cooling system. However, this requires a proper design to ensure that the cooling required to offset solar heat gains does not outweigh energy savings from lighting.

As a result of the extensive development of airport terminals across the globe, the last two decades have seen a worldwide inception of studies (e.g. Greece, UK, China, India) on the evaluation of indoor environmental conditions with implications for energy saving strategies. Balaras et al. took spot measurements of the thermal and lighting conditions in three Greek airports and revealed issues with temperature regulation and humidity controls as well as lack of lighting uniformity, insufficient lighting in certain areas of the buildings and excessive lighting in other as a result of poor solar control. Using a sample of 285 passengers and staff, the study found considerably different satisfaction levels between the two groups with all IEQ parameters. With respect to the thermal environment, for instance, the satisfaction range was 40-70% for employees and over 80% for passengers, similarly to lightings conditions which were satisfactory for about 30% of employees and 40-90% of passengers across the three terminals [5]. Environmental and subjective IEQ data were also collected in eight Chinese airports. The study reported thermal issues such as overcooling in summer and overheating in winter in certain buildings, however underperformance was considerably higher in terms of air quality and acoustics across the terminals surveyed [6]. Another study on IEQ investigated the effect of individual IEQ factors on passenger overall satisfaction using Kano's model [7]. Thermal comfort conditions were highlighted together with space layout as basic factors, indicating that their underperformance has a prominently negative effect on overall satisfaction. On the other hand, lighting conditions were highlighted alongside air quality and acoustic environment as proportional factors denoting that their under- and over-performance have approximately equal strength of influence on overall satisfaction [8].

Investigating thermal comfort conditions in Terminal 1 at Chengdu Shuangliu International Airport, China, Liu et al. undertook physical and subjective measurements over a period of two weeks in summer and winter. The neutral temperature was found at 21.4°C in winter and 25.6°C in summer for passengers and the respective comfort zones at 19.2 - 23.1°C and 23.9 - 27.3°C. The results from 569 questionnaires showed that 78.3% of passengers were generally satisfied with the thermal environment and 95.8% considered the thermal conditions acceptable, concluding that passengers' adaptive ability is very powerful [9]. Microclimatic and subjective data from 128 passengers and staff were also collected in Ahmedabad airport terminal, India, yielding a high comfortable temperature range in the air-conditioned part of the building, 24-32°C [10]. On the contrary, a staff-oriented study in the departures lounge of Suvarnabhumi airport, Thailand, found employees slightly uncomfortable and dissatisfied with the thermal conditions as a result of overheating attributed to the large proportion of glazed roof in the air-conditioned lounge [11]. Another study in three airports in Brazil found the temperature below acceptable levels, which could result in thermal discomfort particularly in occasions of prolonged dwell times [12]. Research on thermal comfort conditions in other building types has highlighted the importance of the duration of exposure [13], demonstrating that discomfort is not viewed negatively if the exposure to it is short [14] or the subject anticipates it is temporary [15].

Thermal comfort criteria are currently provided by ASHRAE and CIBSE. Aiming for an 80% acceptability comfort zone, ASHRAE's design criteria recommend a temperature range of 23.0-26.0 °C and a RH range of 30-40% in winter and 40-55% in summer [16]. CIBSE details seasonal comfort criteria for five terminal areas based on clothing insulation levels and metabolic rate, allowing for varying temperature ranges in different facilities [3]. Recommended illuminance levels in EN 12464 range from 150 lux for general circulation areas (e.g. connecting areas, escalators and travellators) to 500 lux for task-performing areas such as information desks, check-in desks, costums and passport control desks [17].

Despite the wealth of research outputs on the evaluation of environmental comfort conditions in different operational contexts, field research in airport terminals is still in its infancy. Studies are relatively few, often restricted to a single terminal building or a very small number of terminal spaces and as a result findings have been largely fragmented (Table 1). Continuing form the initial assessment of comfort conditions in three airport terminals which revealed a consistent variation of comfort requirements between passengers and staff [18], this paper focusses on the investigation of the thermal and lighting comfort needs of the terminal population as a whole, as to enable designs and energy saving strategies that do not compromise comfort conditions. The study borrows from the methods and procedures of comfort studies in different operational contexts and employs extensive field surveys with a large population sample across the spaces of three airport terminal buildings.

Table 1
Field research on the evaluation of comfort conditions in airport terminal buildings

Study	Location	No. of terminals surveyed	Method	No. of people surveyed	Evaluation of comfort conditions	Highlights
Balaras et al., 2003 [5]	Greece	3	Physical & subjective measurements	285 passengers and staff	• Satisfaction with IEQ parameters	• Problems with temperature regulation, humidity controls and lighting levels/uniformity in certain areas of the terminals. • Different satisfaction levels between passengers and staff with all IEQ parameters.
Babu, 2008 [10]	India	1	Physical & subjective measurements	128 passengers and staff	• Comfortable temperature range	• High comfortable temperature range of 24-32°C in the air-conditioned part of the building.
Liu et al., 2009 [9]	China	1	Physical & subjective measurements	569 passengers and staff	• Neutral temperature • Comfortable temperature range	• High satisfaction with thermal conditions (78%) and high thermal acceptability for passengers (96%); no results reported for staff.
Ramis & dos Santos, 2012 [12]	Brazil	3	Physical measurements	n/a	n/a	• Temperature beyond acceptable levels.
Kotopouleas & Nikolopoulou, 2016 [18]	UK	3	Physical & subjective measurements	3087 passengers, staff and well-wishers	• Neutral and preferred temperature • Acceptable temperature range • Perceived importance of indoor environmental conditions	• Regular discrepancy between experienced and preferred thermal conditions. • Passengers' neutral and preferred temperature is lower than staff's; on average by 1°C and 0.8°C in summer, and by 2.2°C and 1.5°C in winter. • Comfort zone is wider for passengers (6.4°C in summer and 5.8°C in winter) than for staff (4.0°C in both seasons).
Wang et al., 2016 [6]	China	8	Physical & subjective measurements	4800 passengers	• Satisfaction with IEQ parameters	• Overcooling in summer and overheating in winter in certain buildings. • Considerably higher underperformance in terms of air quality and acoustics.
Geng et al., 2017 [8]	China	8	Physical & subjective measurements	3489 passengers	• Satisfaction with IEQ parameters	• Underperformance of thermal environment has a negative effect on overall satisfaction. • Under- and over-performance of lighting conditions, air quality and acoustic environment have almost equal impact on overall satisfaction.
Pichatwatana et al., 2017 [11]	Thailand	1	Physical & subjective measurements	383 employees	• Comparison of simulation results with physical and subjective measurements	• Staff is slightly uncomfortable and dissatisfied with thermal conditions due to overheating attributed to the large proportion of glazed roof in the air-conditioned lounge.

2. Methods and data sources

Three major UK airport terminal buildings of different capacity and typology were surveyed in summer and winter in 2012-2013. The field surveys comprised week-long monitoring of the indoor microclimatic conditions and concurrent questionnaire-guided interviews with occupants throughout the terminal spaces.

2.1 Case study airport terminals

The terminals surveyed are London City Airport (LCY), Manchester Terminal 1 (MAN T1) and Manchester Terminal 2 (MAN T2) (described in detail in Ref. [19]). LCY is a 2-storey compact terminal with total floor area of 10,000 m^2. The building employs the linear terminal concept and has relatively small spaces with little variance in size and design features. It is a business passenger-oriented terminal aiming for fast passenger processing that along its small size and short walking distances provides significantly shorter dwell times which can be down to 20 minutes from check-in to boarding. Nowadays, LCY serves over 4 million passengers a year and is ranked 14th among the busiest airports in the UK [20].

The significantly larger Manchester airport handles over 23 million passengers a year representing the 3rd busiest airport [20]. The passenger-related facilities in MAN T1 and MAN T2 utilise a total area of 43,499 m^2 and 26,063 m^2 offering an annual capacity of 11 and 8 million passengers respectively [21]. The 4-storey MAN T2 building is the newest (1993) among the terminals surveyed. It is a linear structure with gates spread across the two diametrically opposed piers spanning from the central building and features the most contemporary terminal design compared to its peers at Manchester airport. Most of its areas consist of large open-plan spaces with high floor-to-ceiling heights and extensive use of natural light through curtain walls and rooflights. On the other hand, MAN T1 is a 5-storey building with a finger and a satellite pier that has evolved through various expansion and overhaul schemes since its opening in 1962. Accordingly, many of its areas were developed years apart at varying standards resulting in a complex building which comprises an assortment of diverse design trends ranging from the old “boxed up” style to modern spaces.

All three terminals use mechanical ventilation systems. MAN T1 and MAN T2 employed a number of variable refrigerant volume (VRV) systems, fan coil unit systems and direct expansion (DX) systems in smaller areas aiming for a fixed temperature set-point of 21 °C throughout the year. The indoor environment in LCY was controlled by 13 air handling units aiming for the temperature set-points of 20 °C in winter and 23 °C in summer.

2.2 Field surveys

The evaluation of comfort conditions required the investigation of the immediate microclimate occupants experience [22, 23]. Thus, a transportable and easily dismountable microclimatic monitoring station conforming to ISO 7726 [24] was designed to enable movement between airside and landside areas. The station consisted of data logging system, a shielded temperature and humidity probe, an ultrasonic anemometer, a black globe thermometer, a lux sensor and a CO_2 sensor. The monitored parameters included dry bulb and black globe temperature, relative humidity, air movement, horizontal illuminance and carbon dioxide. Most terminal spaces involve predominantly standing and walking activities, thus measurements were taken at the average height of a standing person (1.7 m). All parameters were recorded at one-minute intervals. Due to the large volume of the terminal areas, several monitoring locations were used within every space which were subsequently averaged to provide a representative mean value of the conditions in the space under investigation.

Interviews, using a standardised questionnaire developed for the needs of the study, were carried out in close proximity to the monitoring station to collect subjective data for the evaluation of comfort conditions. The questionnaire [Appendix] consisted of 33 items and used a combination of open-ended, partially closed-ended and predominantly closed-ended questions. Thermal sensation (TS) was evaluated on the 7-point ASHRAE scale while a 5-point scale was used for thermal preference (TP) [25]. A similar form of questions was used for the perception and preference over air movement, humidity and lighting levels. Other data collected include the state of overall comfort, activity level during and 15 minutes prior to the questionnaire (15′ met), clothing insulation, dwell time and demographic data. Interviewees were selected randomly to represent the typical range of terminal users. The field surveys were carried out in check-in areas, security search areas, circulation spaces, retail facilities, departures lounges, gates, baggage reclaim areas and arrivals halls between 5am and 9pm to allow for the daily peak and off-peak occupancy profiles. Further details of the field surveys are given in Ref. [18, 19].

3. Data analysis

The data was analysed with the Statistical Package for Social Sciences (SPSS). A statistical analysis plan was developed to ensure uniformity in data analysis and validity of results. The data analysis was terminal specific in respect to the investigation of lighting conditions and additionally season specific for the evaluation of indoor thermal comfort conditions.

3.1 Indoor microclimatic conditions

The thermal environment in LCY was characterised by a very narrow temperature range of approximately 4 °C in summer and winter, and uniformity between the majority of spaces, indicative of its spatial uniformity and compact design. The lowest and highest temperatures were observed during the low occupancy and peaks respectively. A uniform thermal environment was also found in MAN T2, where however the operative temperature presented a wider range (20.6 - 26.3 °C in summer and 18.9 - 24.5 °C in winter) and all spaces were 1.1 - 3.6 °C cooler in winter when there were prolonged periods of time with very low occupancy. On the other hand, the thermal conditions in MAN T1 were significantly different. As a result of its diverse spaces, the terminal was seen to house a variety of thermal environments as well as the widest temperature range (19.1 - 25.4 °C) in summer and 16.2 - 25.6 °C in winter) and the highest mean temperature differences (up to 6.2 °C) between its spaces.

Air movement was particularly low in all three terminals, resulting in average values within the range of 0.1 - 0.2m/s. Air movement exceeding the upper comfort boundary of 0.3m/s occurred sporadically in certain spaces exposed to outdoor wind through openings (e.g. gate lounges in LCY and arrivals hall of MAN T1). The mean RH (%) levels were within the ASHRAE recommended range, in spite the lack of (de)humidification control strategy in the buildings. The CO_2 concentration was on average well below the ASHRAE recommended maximum concentration range of 1000-1200ppm [26], denoting adequate ventilation rates in all cases (fig. 1).

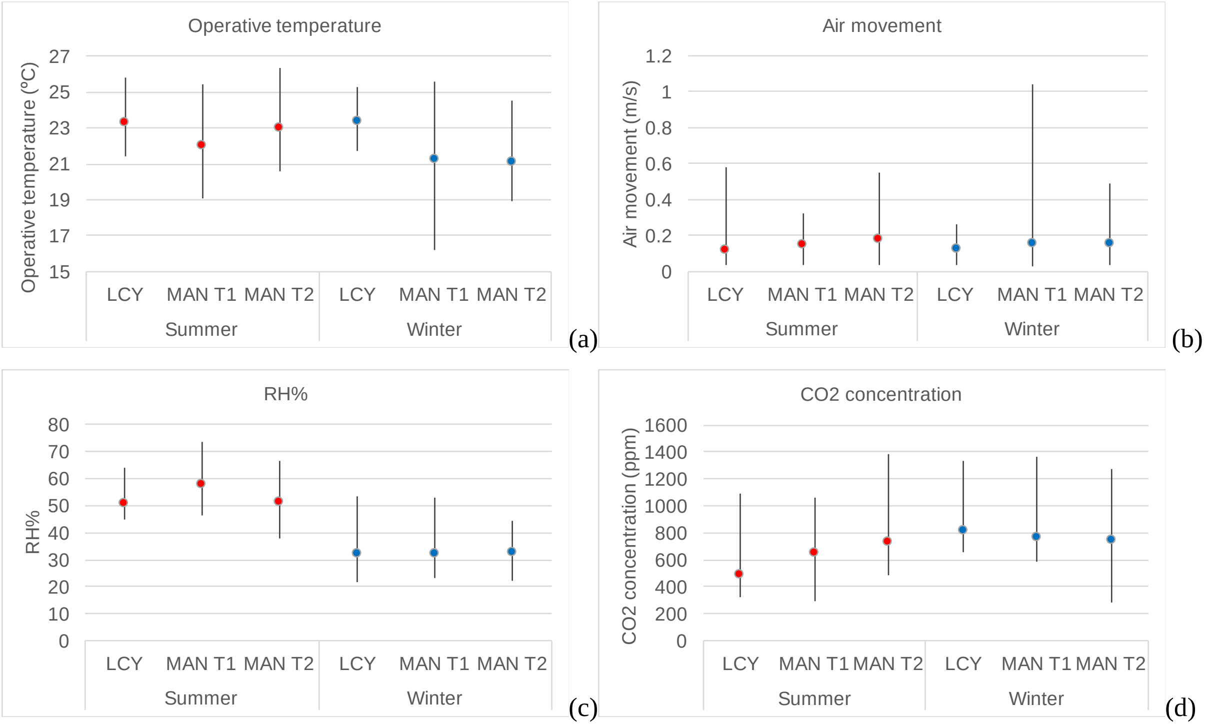

Fig. 1. Minimum, mean and maximum (a) operative temperature, (b) air movement, (c) RH% and (d) CO_2 concentration.

3.2 Description of the sample population

A total of 3,087 people were interviewed in the surveyed terminals. The sample population presented a 50:50 male-female ratio and comprised staff, passengers, well-wishers and other short-stay visitors (Table 2). Passengers, 2333 in total, represented 74-80% of the sample population at each terminal consisting predominantly of departing (91-97%) and secondarily from arriving passengers (3-9%). The profile of departing passengers varied in terms of type and dwell time between the terminals. About half (52%) in LCY were travelling on business, whilst the respective fraction was considerably lower MAN T1 (14%) and MAN T2 (3%). In respect to dwell time, nearly 80% of passengers flying from LCY had spent up to an hour airside and 40% no more than 30 minutes. The latter was true for only 19% and 14% of the passengers departing from MAN T1 and MAN T2, where dwell time for the majority exceeded an hour.

Table 2
Number and type of interviewees in the surveyed terminals.

	LCY		MAN T1		MAN T2		Total
	Summer	Winter	Summer	Winter	Summer	Winter	
Employees	68	72	103	71	65	86	465
Passengers	320	332	462	425	406	388	2333
Well-wishers & other	15	11	98	39	67	59	289
Total	818		1198		1071		3087

A wide range of employees, 465 in total, were interviewed in their workspace and accounted for 14-17% of the sample population at each terminal. Representative of personnel's dwell time, about 80% were full-time employees and 20% was working part-time. Well-wishers and other short stay visitors were studied in check-in and arrivals halls and represented 3-12% of the terminals' sample population.

3.3 Clothing insulation levels

Clothing insulation was determined using the detailed clothing data collected from each interviewee during the questionnaire and the insulation values for separate garment pieces provided in ISO 9920 [27]. The mean clothing insulation was in the range of 0.5-0.6 clo in summer and higher between 0.9 clo and 1.1 clo in winter (Table 3).

Table 3
Mean values and standard deviation of clothing insulation (clo).

	LCY		MAN T1		MAN T2	
	Summer	Winter	Summer	Winter	Summer	Winter
Mean	0.64	1.11	0.55	0.99	0.51	0.89
SD	0.19	0.27	0.15	0.28	0.13	0.24

The data analysis showed that outdoor – rather than indoor temperature – have a higher impact on the clothing levels worn in the terminals, largely a result of passenger dominance in the sample population. While the relationship between operative temperature and clothing insulation was statistically insignificant in most cases, outdoor temperature was found to explain about 50% of the variance in clothing levels worn indoors (Fig. 2). The mean daily temperature (24h-average) during the summer surveys fluctuated between 11.0-20.0 °C for LCY, 15.0-16.0 °C for MAN T1 and 10.0-16.0 °C for MAN T2. The respective ranges during the winter surveys were 3.9-12.0 °C, 0.9-6.6 °C and -1.6-6.3 °C.

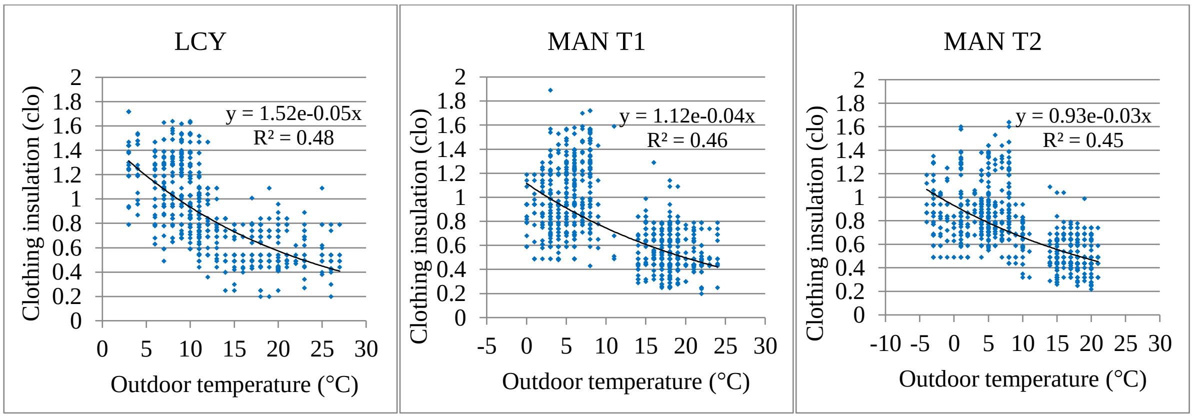

Fig. 2. Relationship between clothing insulation and outdoor temperature.

3.4 Evaluation of thermal comfort conditions

3.4.1 Thermal sensation and preference

Correlation analysis indicated that TS and TP correlates better with operative temperature than with any other of the physical variables, with the associated Pearson coefficients (r) in the range of 0.2-0.4 ($p<0.01$) and 0.3-0.4 ($p<0.01$) respectively. Fig. 3a illustrates the frequency distribution of TS for each terminal surveyed. Most of the interviewees in LCY (83%) and MAN T1 (78%) were represented from the middle three categories of the ASHRAE scale in summer, when "neutral" was the sensation with the highest percentage and the average TS was 0.5 and 0.4 respectively. Because of the higher clothing insulation in winter, the majority of TSs (87% in LCY and 76% in MAN T1) shifted towards warmer votes, resulting in mean TS of 0.9 in LCY and 0.6 in MAN

T1. This pattern was similar in MAN T2 in both seasons, with the average TS at 0.6 and 0.5 in summer and winter.

Unlike TS, the profile of TP was very similar across the terminals, with approximately 50% of interviewees preferring no change and nearly 40% preferring cooler conditions (Fig. 3b). In winter, the majority (53%) in LCY preferred cooler conditions suggesting an issue with overheating. In MAN T1 almost half found the thermal environment ‘just right’, however the percentage of those preferring to be warmer was almost twice of that in summer. MAN T2 presented the greatest thermal satisfaction from all terminals as nearly 60% of interviewees required no change.

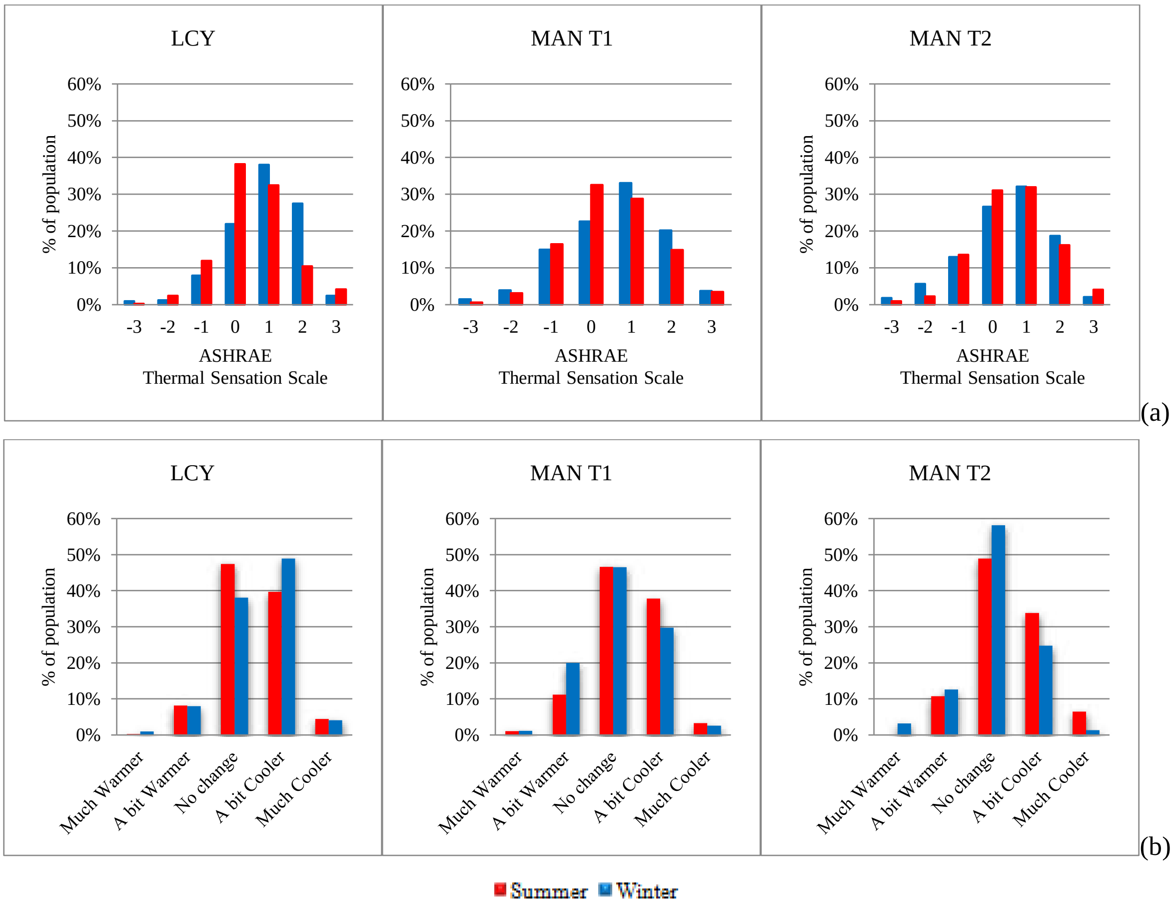

Fig. 3. Percentage distribution of (a) thermal sensation and (b) thermal preference votes in summer and winter.

Further scrutiny of the TS and TP data revealed that neutral (i.e. neither cold nor hot) was not the desired thermal state for a significant fraction of the sample population, in most cases for over half the interviewees. The analysis assumed that preference for “no change” denotes satisfaction with the experienced conditions. The number of interviewees who had called for no change on the TP scale ranged between 158 in LCY, in winter, to 310 in MAN T2, also in winter. Using these sample populations, the results showed that 59% of the interviewees in LCY, 67% in MAN T1 and 63% in MAN T2 who were satisfied with the thermal conditions in winter were at a thermal state other than neutral (Fig. 4). Similarly, in summer, 45% of the interviewees in LCY, 59% in MAN T1 and 54% in MAN T2 who required no change had reported a TS other than neutral. In both seasons, the “preferred” thermal state among the interviewees satisfied with the thermal conditions while at non-neutral sensation was “slightly warm”. In summer, the “slightly warm” percentage was in the range of 24-29%

and higher at 33-38% in winter when this thermal state was preferred from a similar fraction of people preferring to be neutral. Moreover, a relatively high percentage of people in winter, 11-19%, was found satisfied with the thermal conditions while feeling "warm". Most of these cases were derived from entry spaces such as check-in halls and arrivals halls. This highlights the considerable impact outdoor weather conditions may have on comfort conditions in such facilities as well as the influence of transition thermal perception on how occupants evaluate indoor environments, especially in situations of temporary occupancy [28].

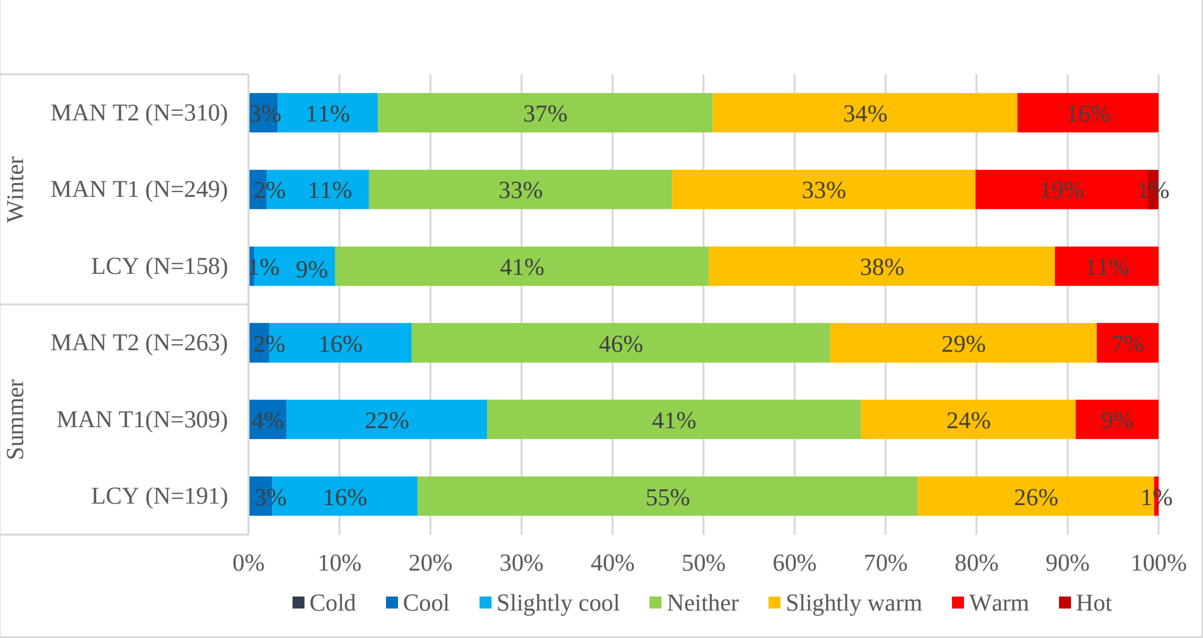

Fig. 4. Percentage distribution of thermal sensation from interviewees preferring no change of the thermal conditions.

TS and TP were further assessed against the subjective assessment of overall comfort to investigate potential links between the perceived thermal conditions and overall comfort. The percentage distribution of comfortable against TS and TP yields a bell-shaped curve demonstrating that the thermal environment had an impact on occupants' overall comfort in airport terminals. Comfort was seen to decline the further away from neutral the sensation was (Fig. 5a) and the further from "no change" the preference drifted away (Fig. 5b).

The results are also indicative of occupants' tolerance of conditions deemed as uncomfortable; the percentage of comfortable was higher than 80% when TS was within the middle three categories of the ASHRAE scale and in spite of its drop when TS= ±2 the majority of occupants would be still comfortable, while the impact of thermal environment on comfort would be significant only when the conditions were deemed as cold or hot. In addition, the sharper drop of percentage of comfortable at "warm" and "hot" sensations (TS=2, 3), as compared to that of "cool" and "cold" sensations (TS=-2, -3) indicates a higher sensitivity to warmer conditions. Similarly, the percentage of comfortable was over 80% or close to 80% when TP was within the middle three categories, dropping significantly only when much warmer or much cooler conditions were required.

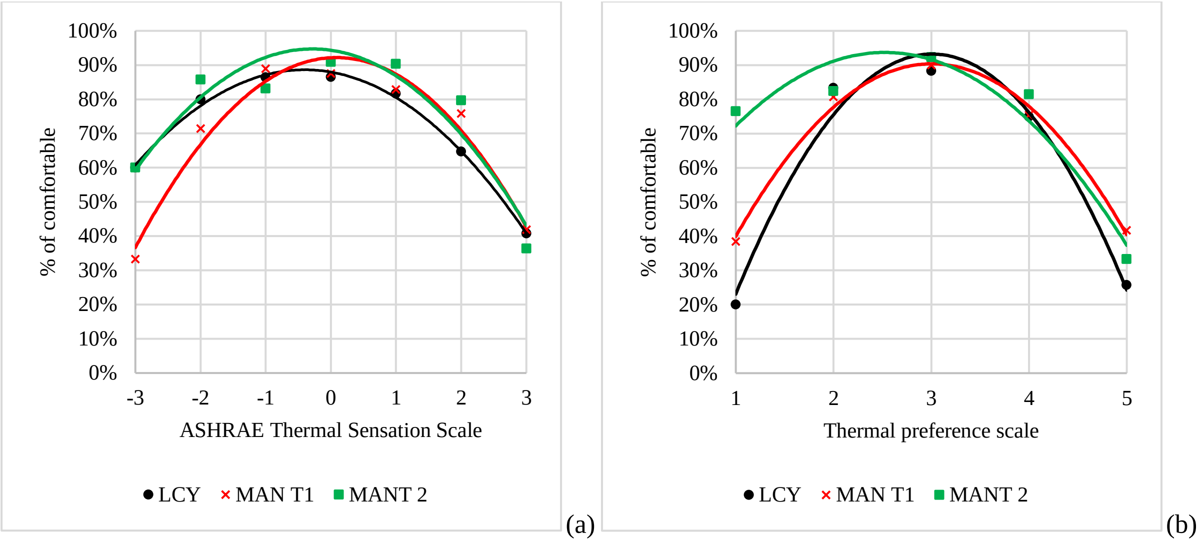

Fig. 5. Percentage of comfortable at each (a) thermal sensation and (b) thermal preference category (from 1=much warmer to 5=much cooler).

3.4.2 Subjective assessment of air movement and humidity

Air movement sensation and preference were assessed on a 5-point scale from “very low” to very high” and from “much more” to “much less” respectively. The correlation of both subjective assessments with air movement was weak; Pearson correlation coefficients ranged between 0.1 and 0.2, p<0.01, largely a result of the very low air movement across the terminals (Fig. 1b). In the absence of perceptible air movement, occupants tended to assess air movement through a temperature evaluation. In fact, air movement sensation and preference were seen to correlate better with operative temperature than with any other of the physical variables. The Pearson coefficients, significant at p<0.01, ranged from -0.34 to -0.11 for sensation and from -0.30 to -0.14 for preference, indicating that occupants tended to assess air movement as low at higher temperature levels and to prefer more air movement the higher the temperature was sensed.

The most frequent assessments were “low” and “neither low nor high”, with the two cumulatively representing 70-80% of the responses (Fig. 6a). The distribution of preference votes (Fig. 6b) shows that nearly half the people in the three terminals found air movement just right, while “a bit more” was widespread among those requiring a change. Such preference was expressed by over 30% in MAN T1 and MAN T2, and by nearly half the interviewees in the warmer LCY.

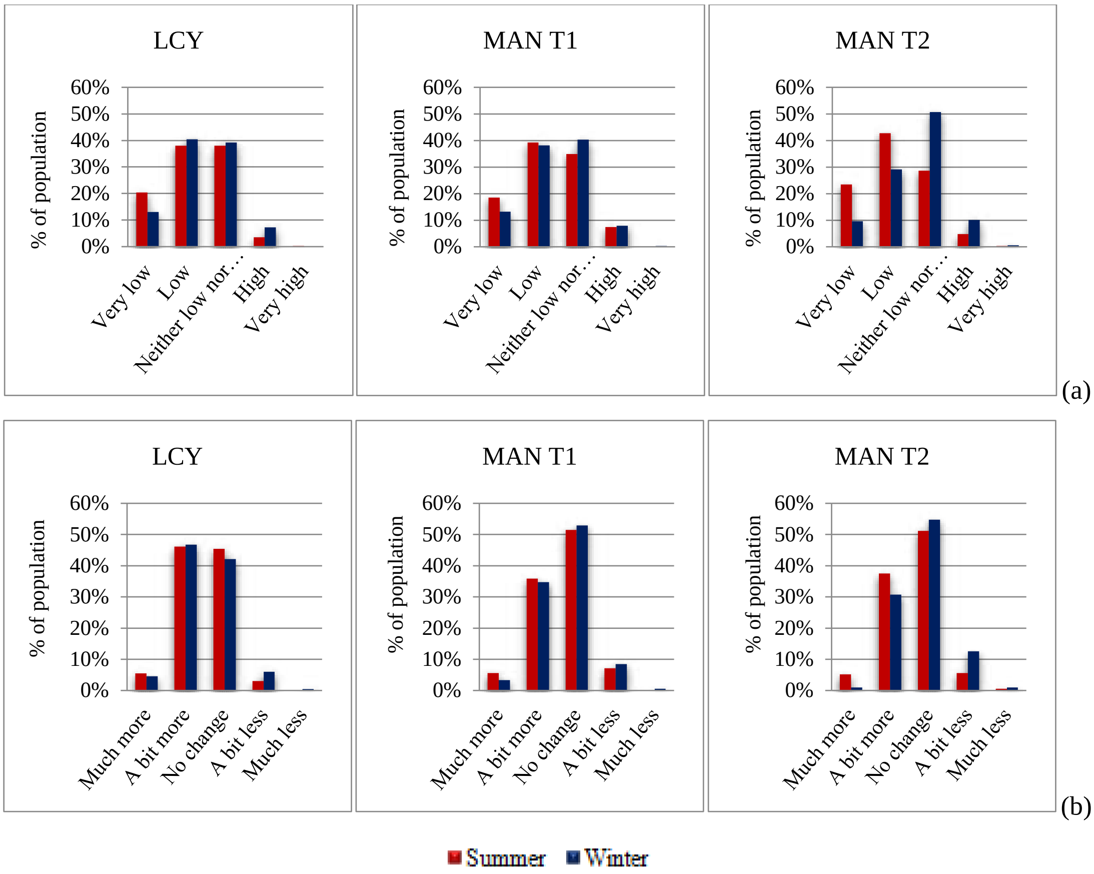

Fig. 6. (a) Sensation and (b) preference over air movement (sensation of "very high" and preference for "much less" air movement are below 1%)

The sensation of humidity was assessed on a 3-points scale. The majority of interviewees in summer (61-75%) and winter (58-63%) assessed the conditions as "neither damp nor dry". The sensation of dryness in winter was increased as noted by nearly 33% of people in LCY and MAN T1, while such notion was expressed by 33% of respondents in MAN T2 in both seasons. The sensation of humidity was better correlated with RH%. The correlation coefficients, -0.17 for LCY and -0.18 for MAN T1, $p<0.01$, verify interviewees' assessment, implying drier sensations the drier the environment was. To investigate change rate of humidity sensation, RH% was binned in 5% increments and the mean sensation score was calculated for each bin and regressed against RH%. The regression models were significant at the 99% level or better (Fig. 7). Representing the change rate of humidity sensation, the slope of the regression models indicates that sensation would not be altered with the small variance of RH% observed in the terminals during the summer and winter monitoring periods.

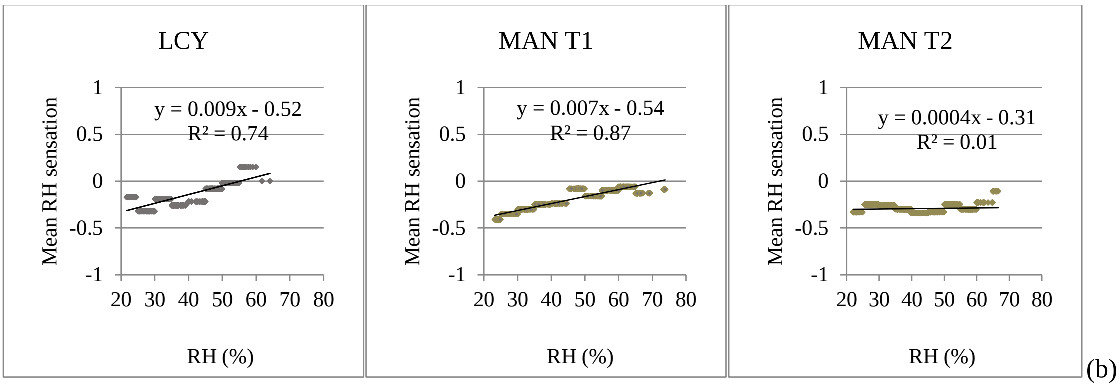

Fig. 7. Relationship between mean RH sensation (from -1 = dry to +1 = damp) and RH (%)

3.4.3 Comfort temperatures

This section presents the calculation of comfort temperatures, including neutral and preferred, and the determination of acceptable temperature ranges. Neutral temperature denotes the temperature yielding a sensation of neither hot nor cold [29] whereas preferred temperature associates preference votes with the temperatures experienced and represents the thermal point at which neither cooler nor warmer conditions are preferred [30, 31].

The comfort temperatures were determined by means of weighted linear regressions[1], using half-degree increments of operative temperature [33]. For the calculation of neutral temperatures, the mean TS score was determined for each bin and regression models were fitted between mean TS and operative temperature. Neutral temperature was then derived from solving the regression equations for TS = 0. The regression models were also used for the evaluation of the operative temperature ranges in which 80% and 90% of terminal users would find the thermal conditions acceptable, in accordance to the statistical assumptions underlying the PMV/PPD heat-balance model [34]. The models (Fig. 8) achieved a statistical significance level of 99% or better.

The results showed similar thermal sensitivity across the terminals in summer and wide differentiation in winter (Table 4). As the slope of the regression models suggest, a unit increase of TS in summer would require a temperature rise of 3.9 ºC in LCY, 3.4 ºC in MAN T1 and 3.5 ºC in MAN T2. In winter, thermal sensitivity was increased in LCY resulting in a TS change rate of one unit for every 2.2 ºC temperature change. In MAN T1 this remained essentially unchanged, while the reduced thermal sensitivity in MAN T2 indicates that the mean TS would not be altered with temperature changes below 6.2 ºC.

The neutral temperatures were in the range of 20.4-21.4 ºC in summer and 18.3-21.5 ºC in winter, consistently lower than the mean operative temperature occupants experienced in all three terminals (Table 4). In summer, this was lower by 1.6 ºC in MAN T1 and by 1.9 ºC in LCY and MAN T2. Despite the increased thermal sensitivity in LCY during winter, the neutral temperature and the difference from the mean operative temperature remained unchanged, while thermal neutrality in MAN T1 and MAN T2 was achieved at temperatures 1.9 ºC and 2.8 ºC below the mean operative temperature respectively.

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[1] The calculation of preferred temperatures involved Probit analysis which although confirmed the results obtained from linear regression, was ineffectual in cases where the temperature range was very narrow. The alternative method of linear regression was used to retain uniformity in data analysis (Personal communication with Humphreys M.A.[31]).

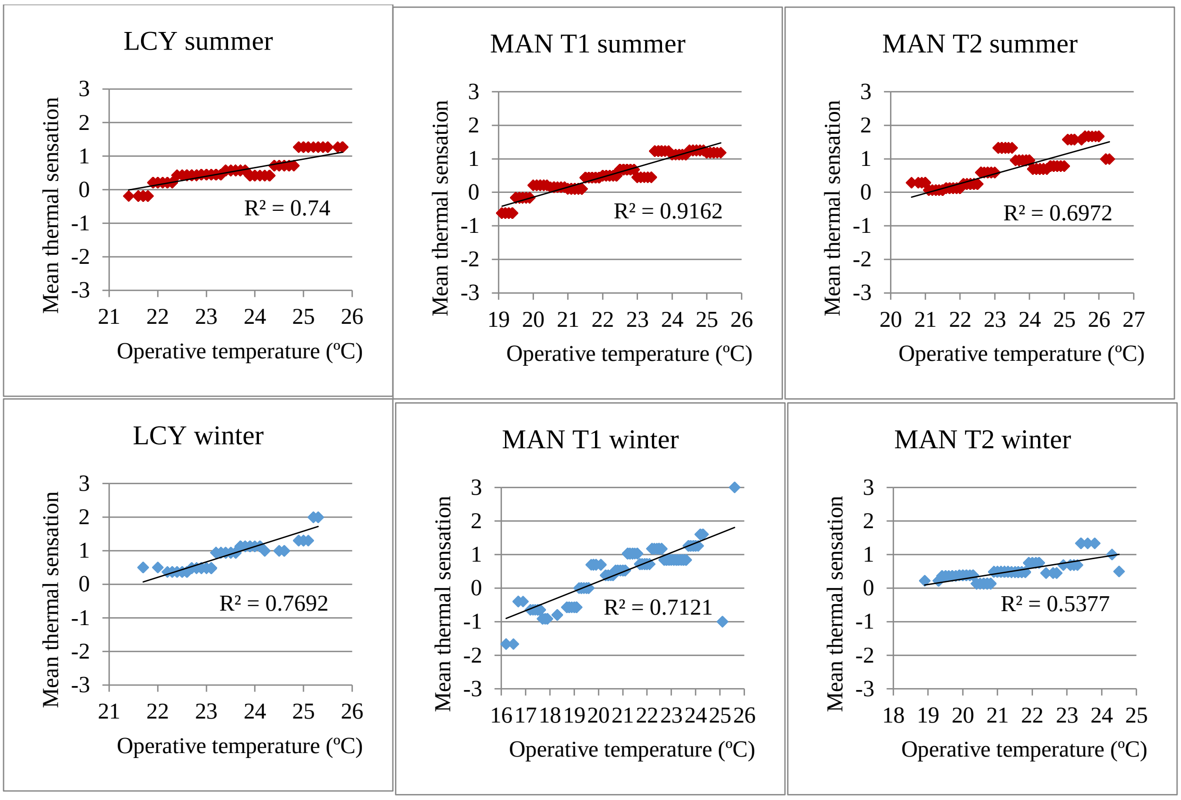


Fig. 8. Relationship between thermal sensation and operative temperature in summer and winter.

The calculation of preferred temperatures involved the transformation of the 5-point thermal preference variable (Fig. 6b) into a 3-point variable, so that “prefer warmer” represents the preferences for a “much warmer” and “a bit warmer” environment and “prefer cooler” the “much cooler” and “a bit cooler” votes. The percentages of “prefer warmer” and “prefer cooler” were calculated for each 0.5 ºC increment of operative temperature while using the sample size of each bin as weighting factor. Separate linear regression models were fitted between the “prefer warmer” and “prefer cooler” percentages and the operative temperature, with the intersection of the two regression lines (Fig. 9) designating the preferred operative temperatures.

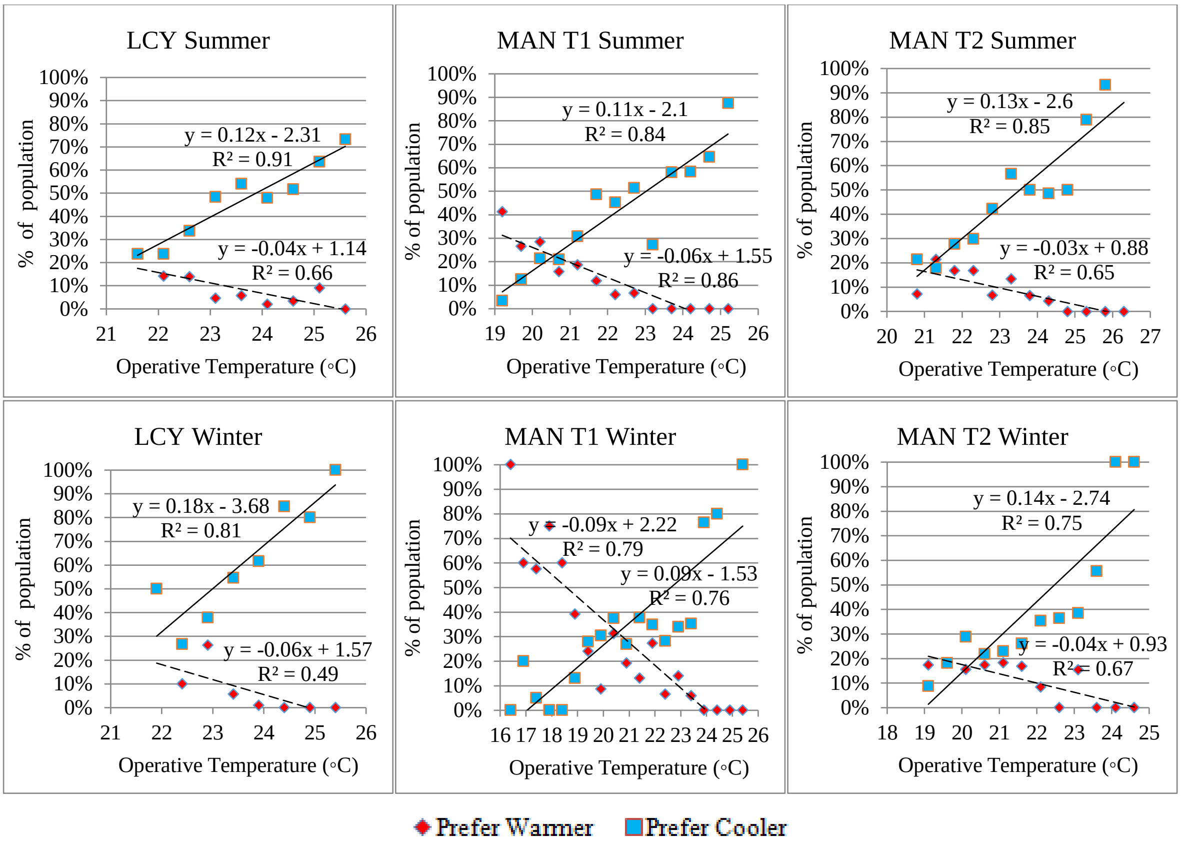


Fig. 9. Calculation of preferred temperatures for summer and winter.

Preferred temperatures were in the range of 20.9-21.3 ºC, presenting insignificant seasonal variation and most often coinciding with neutral temperatures (Table 4). The relative consistency of preferred temperatures implies behavioral adaptation in the form of clothing adjustments, which given the significant influence of outdoor conditions on clothing levels (Fig. 2) pushes the preferred temperatures together. The results demonstrate a preference for cooler conditions than the ones experienced in both seasons across the terminals (Table 4). In LCY, the preferred temperature was 2.0 ºC lower than the mean temperature in summer and winter, and in both cases below the lowest temperature recorded (Fig. 1), thus providing further evidence of overheating which according to the TP votes (Fig. 6b) was more pronounced in winter, and highlighting the need for less heating. The gap between experienced and preferred temperatures was of a similar magnitude in MAN T1 and MAN T2 in summer, when occupants preferred 1.4 ºC and 2.0 ºC cooler temperature respectively, and smaller at about 1.0 ºC in both terminals in winter. Moreover, the results provide evidence of tolerance under cooler conditions. In MAN T1 and MAN T2, where the lowest indoor temperatures occurred during the winter surveys, the preferred temperature was 20.6 ºC and 20.2 ºC while neutral temperature was 19.4 ºC and 18.3 ºC respectively, indicating that occupants would still be comfortable at temperatures lower than the ones preferred.

Table 4

TS regression models, neutral and preferred temperatures (°C) and acceptable ranges in summer & winter.

		Slope	Constant	R^2	Tmean (°C)	Tneutral (°C)	Tpref. (°C)	80% accept. (°C)	90% accept. (°C)
Summer	LCY	0.256	-5.49	0.74	23.3	21.4	21.3	18.1 – 24.8	19.5 – 23.4
	MAN T1	0.300	-6.13	0.92	22.0	20.4	20.6	17.6 – 23.3	18.8 – 22.1
	MAN T2	0.289	-6.11	0.70	23.0	21.1	21.0	18.2 – 24.1	19.4 – 22.9
Winter	LCY	0.459	-9.88	0.77	23.4	21.5	21.3	19.7 – 23.4	20.4 – 22.6
	MAN T1	0.288	-5.58	0.71	21.3	19.4	20.6	16.4 – 22.3	17.6 – 21.1
	MAN T2	0.163	-2.99	0.54	21.1	18.3	20.2	13.1 – 23.6	15.3 – 21.4

*Figures in italic indicate comfort zone limit values beyond observed temperature range.

3.5 The lighting environment

3.5.1 Overall lighting conditions

Data in respect to the overall lighting environment were collected on a 7-point scale from “very dim” to “slightly bright” for sensation (LS) and on a 5-point scale from “much dimmer” to “much brighter” for preference (LP). Correlation analysis showed a correlation of the order of 0.20-0.30, $p<0.01$ between LS and illuminance and a negative correlation in the range of 0.10-0.20, $p<0.01$ between LP and illuminance. Most of the LS votes (about 80%) were within the middle three categories in LCY and MAN T1, where more people assessed the lighting conditions as “neither bright nor dim” and “slightly dim” respectively. On the contrary, the majority of votes (57%) in MAN T2 was on the bright side of the 7-point scale with conditions perceived mostly as “bright” as a result of the contemporary terminal design with extensive sources of natural light (Fig. 10a). Unlike the differentiated LS profiles, the profile of preference votes was similar across the terminals with the majority (60-67%) finding lighting “just right” and preference for brighter conditions being dominant among those requiring a change (Fig. 10b). Further representative of the preference for a bright environment is that while 15% of the interviews in LCY and MAN T1 and 32% in MAN T2 found the conditions “bright” and “very bright”, only 0.2% in MAN T1 and MAN T2 and 1.5% in LCY (i.e. 12 people) required “much dimmer” conditions, representing in all cases interviewees sitting near windows and curtain walls during sunshine hours.

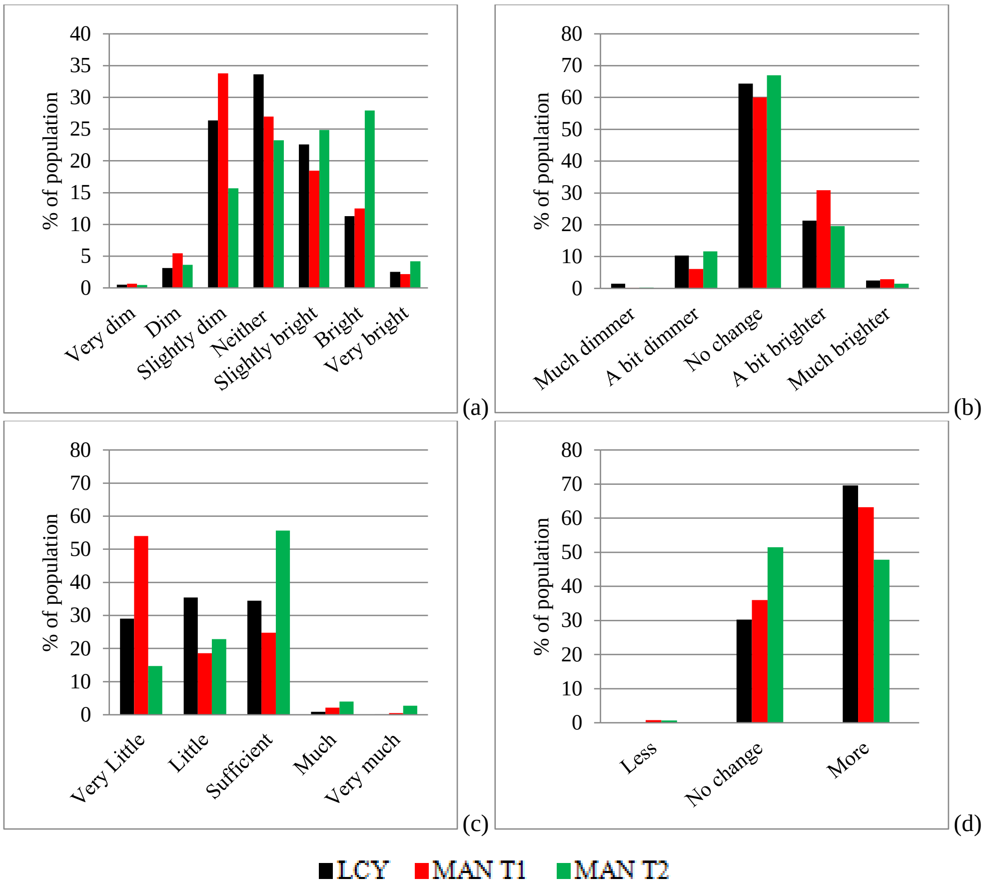


Fig. 10. Percentage distribution of (a) lighting sensation, (b) lighting preference, c) assessment of daylight and d) daylight preference.

The investigation of LS against illuminance yielded a logarithmic relationship between the two. Working with increments of 200 lux and the respective mean scores of LS, the latter was found well clustered around the logarithmic line for illuminance up to 1000 lux and significantly variant at higher levels of illuminance (Fig. 11a). The mean LP was also found logarithmically related to illuminance. With only few points denoting a preference for “a bit dimmer” environment at very high illuminance levels, the mean LP scores remain close the “no change” line demonstrating a consistent preference for a bright environment (Fig. 11b).

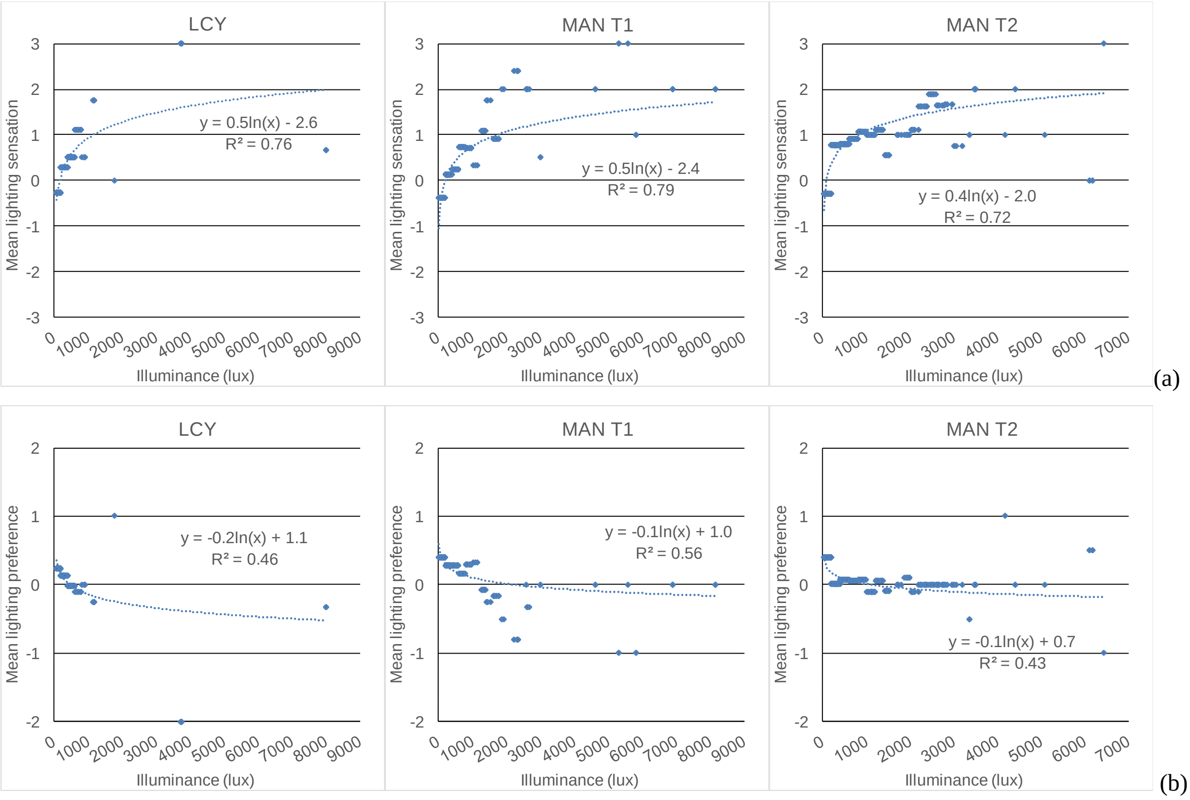


Fig. 11. Relationship between (a) mean lighting sensation (from very dim=-3 to very bright=3) and (b) mean lighting preference (from much dimmer=-2 to much brighter=2) with illuminance.

This was further stressed from the cross-examination of LS and LP (Fig. 12). The line representing the mean LP denotes a preference for brighter conditions when lighting was deemed to be “very dim”, “dim” and “slightly dim” and a preference for “no change” when lighting was assessed as “neither bright nor dim”, “slightly bright” and “bright” demonstrating that a bright rather than a dim lighting environment was preferred in all terminals, while indicating a preference for “a bit dimmer” conditions only when lighting was perceived to be “very bright”. Moreover, the lack of a clear distinction between “slightly bright”, “bright” and “very bright” in terms of illuminance (Fig. 11a) suggests that satisfaction with the lighting environment - as expressed via the preference for no change (Fig. 11b) - was more dependent on the perceived conditions rather than the actual illuminance.

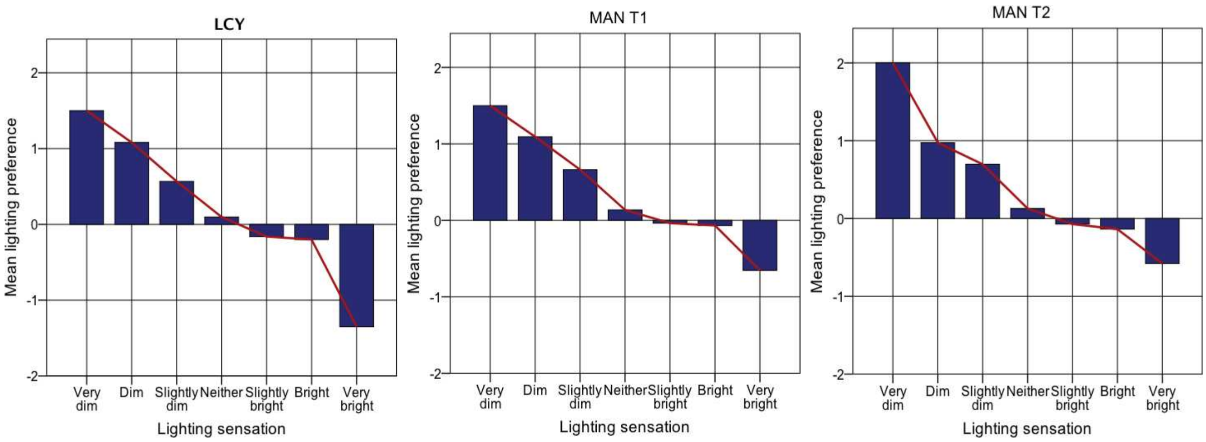


Fig. 12. Mean lighting preference (line, from much dimmer=-2 to much brighter=2) against mean lighting sensation (bars).

3.5.2 Daylight

The perception and preference over the amount of natural light was recorded on a 5-point (from “very little” to “very much”) and 3-point scale (from “prefer less” to “prefer more”) respectively in spaces with at least some basic source of natural light during daytime hours. The data analysis revealed three distinct perception distributions (Fig. 10c), indicative of the different daylight profiles of the terminals. The assessments of natural light in LCY were almost equally distributed between the categories “very little”, “little” and “sufficient”, each representing approximately a third of the sample population. The assessment of natural light as “very little” by over half the interviewees in MAN T1 reflects the limited sources of natural light, existent only in certain spaces of the terminal, while a similar fraction of interviewees in the highly glazed building fabric of MAN T2 found the natural light “sufficient”. The corresponding preference votes demonstrated people’s desire for natural light (Fig. 10d). Preference for more daylight was widespread among interviewees in LCY (70%) and MAN T1 (65%), while the desire was further highlighted in MAN T2, where although the majority acknowledged the sufficiency of natural light in the building (“sufficient”, “much” and “very much” accounted together for 62% of responses; Fig. 10c), nearly half the interviewees would prefer even more and almost no one less.

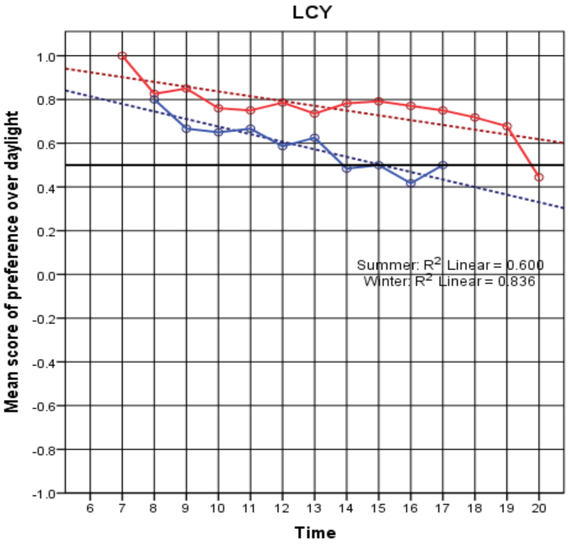
The preference for daylight was evaluated against time of the day to investigate a potential link between the two. The underlying assumption was that travellers were from the same time zone as the overwhelming majority was departing passengers. The mean preference scores were calculated for each hour of the daytime (averaged for all days of each survey) and regressed against time, separately for summer and winter. The data used in this analysis were collected between the representative sunrise and sunset times (Fig. 13) and involved approximately 80% of the total sample population from each case study, interviewed during these periods. For all terminals, the mean preference was seen to range between “1=more” and “0=no change” while never approaching “-1= less”, highlighting from a different perspective the desire for natural light. The plots between mean preference and time (Fig. 13) demonstrate a high score of preference for more daylight in the morning hours, which declines later on the day and turns into a preference for “no change” towards the sunset, indicating that preference scores declined the late the time in the day was. This seems to suggest that preference for natural light follows the endogenous clock associated to the light-dark cycle. Having assumed a linear relationship, the R^2 values show that the variable “time” explains about 80% of the variance in people’s mean preference over natural light during the daytime hours.

The trend was similar between the terminals, however, the change rate of preference varies considerably as the cut-off point of time beyond which the preference for “no change” prevails differs. For instance, the preference for more daylight in LCY during the winter surveys declines gradually during the day and crosses the line at 0.5 (thus becoming preference for “no change”) at 2pm; i.e. 3 hours before the sunset. For MAN T1 this occurs 2 hours prior to nightfall, whereas in MAN T2 “no change” prevails 7 hours before the sunset, since 9am. Similarly, in summer, preference for more daylight was eliminated an hour before the sunset in LCY and MAN T1 whilst for MAN T2 this was 6 hours. The sharper drop of the mean preference and therefore the earlier appearance of the “no change” preference in MAN T2 in summer and winter can be associated to the profusion of natural light across the terminal’s spaces.

Sunrise/sunset times during the surveys

	Sunrise / sunset times*	
	Summer	Winter
LCY	4:50 / 21:08	7:39 / 16:50
MAN T1	6:06 / 20:14	8:10 / 15:50
MAN T2	6:20 / 19:55	8:19 / 15:50

*Representative times from the median day of the surveys, data from www.sunrisesunsetmap.com [35]



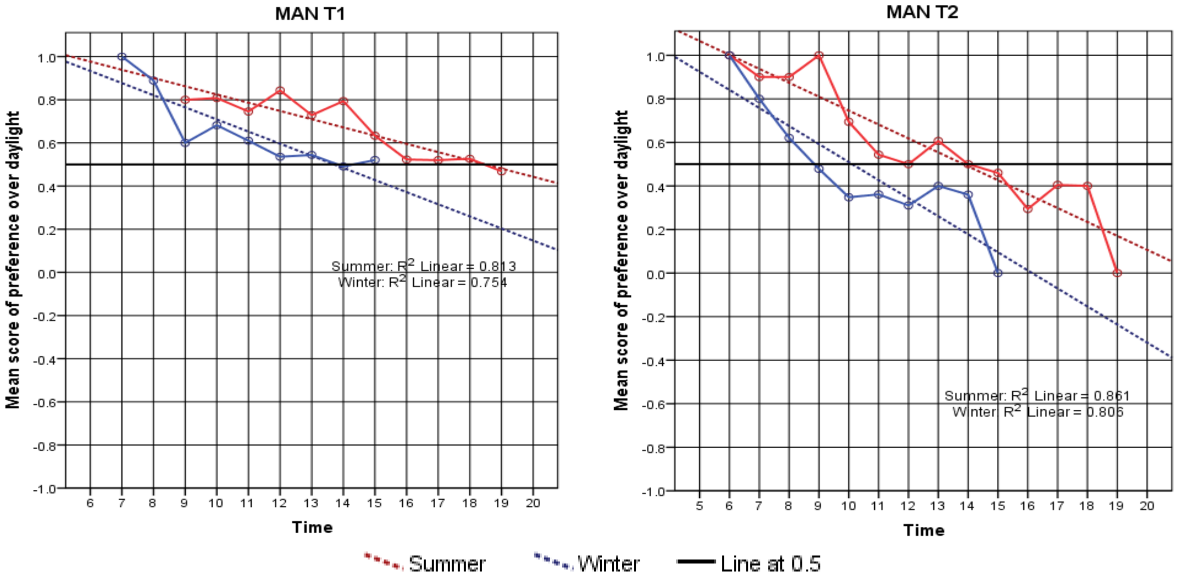


Fig. 13. Mean score of preference for natural light (-1 = prefer less, 0 = no change, 1 = prefer more) in summer and winter. Dotted lines are linear regression lines. Points between 0 and 0.5 denote "no change", while points between 0.5 and 1 denote a mean preference for more natural light.

3.6 Environmental vs. non-environmental comfort parameters

Using two open-ended questions, the study collected data regarding the terminal attributes occupants liked and disliked the most. The data were used to assess the perceived importance of the indoor environmental conditions compared to typical concerns in such facilities. The underlying assumption for the analysis was that an individual who reports to (dis)like a certain condition the most views that condition as important.

The responses were primarily classified into "environmental" (thermal, lighting, acoustic environment and air quality), "non-environmental" (all other issues) and "nothing particularly". A considerable fraction of interviewees (23-50%) raised no issues, largely a result of passengers' view of the terminal as a short-term transition from landside to airside, while a higher percentage (41-77%) highlighted non-environmental attributes such as seating, amount of space/crowding and speed of processing/queues (Fig. 14). The environmental conditions were highlighted positively by a low percentage of interviewees (6-15%) and negatively by a higher percentage (15-23%), implying that the negative impact of the indoor environment on overall comfort is stronger than the positive one and that the indoor conditions were not considered important unless expectations were not met. The breakdown of attributes disliked the most (Fig. 15a) found the thermal environment ranked 2nd in LCY and MAN T2 and 3rd in MAN T1, with relevant issues raised by approximately 10% of the interviewees at each terminal. Representative of their impact on overall comfort, thermal conditions were ranked 1st among the interviewees who had reported an “unacceptable” TS (i.e. ±2, ±3), yet the respective percentage (22-30%) was low indicating high levels of tolerance of thermal conditions (Fig. 15b).

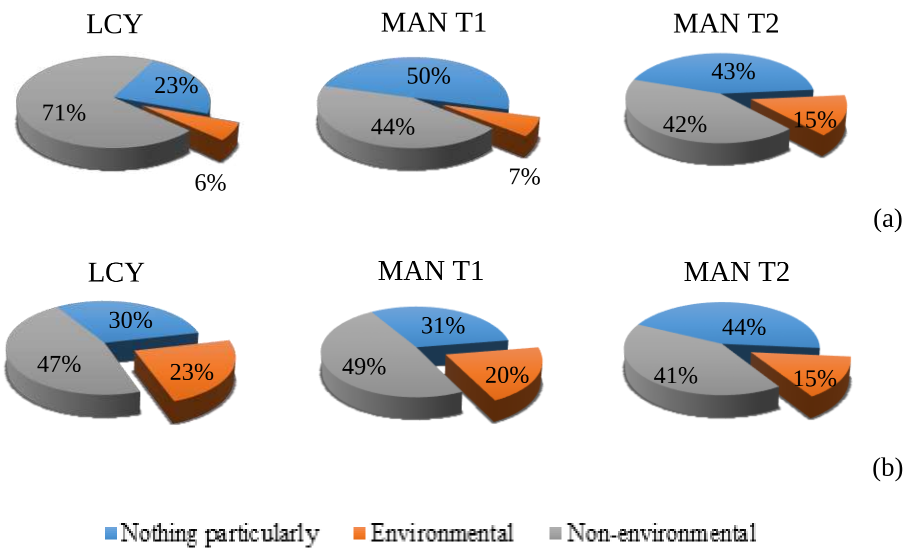


Fig. 14. Attributes of the terminal interviewees (a) liked the most and (b) disliked the most, classified into environmental and non-environmental and nothing particularly.

Moreover, the results suggest that lighting conditions were perceived as the second most important parameter of the indoor environment, ranked 5th among the most disliked attributes of LCY and MAN T2 and 4th in MAN T1, with relevant issues raised by 5-10% of interviewees at each terminal (Fig. 15a). The relatively high percentage of people found mostly pleased with the indoor environment in MAN T2 (15%; Fig. 14a), was predominantly due to “lighting” and particularly due to the abundance of natural light in most spaces. In fact, MAN T2 was the only building where an environmental factor was viewed positively, receiving also a rank higher than the non-environmental parameters.

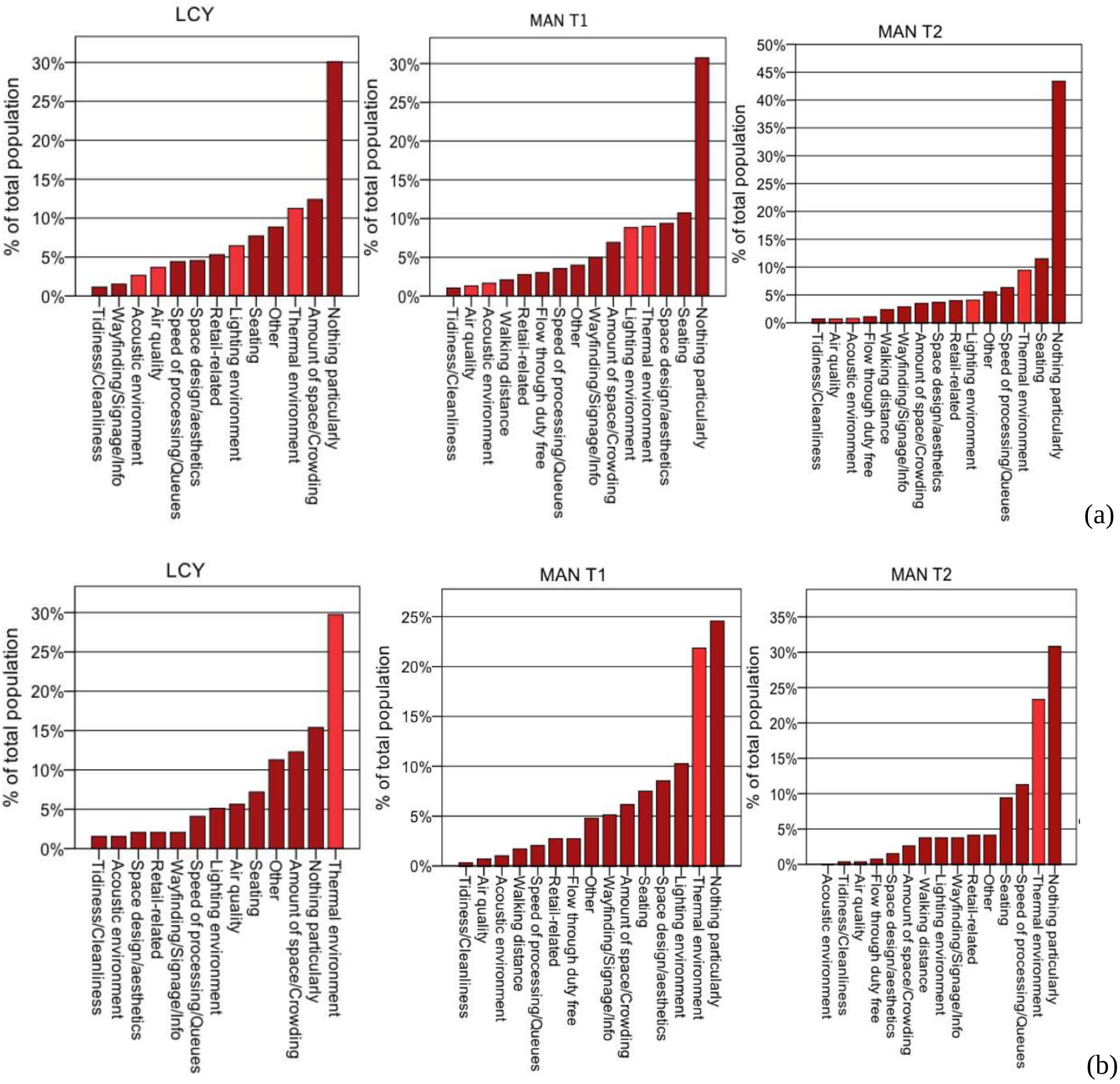


Fig. 15. Specific attributes of the terminal buildings people disliked the most (a) overall and (b) when thermal sensation was ±2, ±3.

4. Discussion

The analysis of physical and subjective data from 3,087 passengers, staff and well-wishers from three airport terminals revealed a consistent discrepancy between the indoor thermal conditions and people's thermal requirements. Over half the interviewees in most cases preferred thermal conditions different to the ones experienced, with the preference for cooler conditions (Fig. 3b) and higher air movement (Fig. 6b) dominating in summer and winter. The results showed that cooler temperatures by 0.7-2.1 °C were preferred while thermal neutrality was 1.6-1.9 °C lower than the mean indoor temperature in summer and lower by 1.9-2.8 °C in winter (Table 4). For the smaller and compact terminal at LCY airport, the high percentage of people preferring a cooler thermal environment (44% in summer and 53% in winter; Fig. 3b) and the fact that comfort temperatures were below the narrow temperature range of terminal (Fig. 1 & Table 4), suggest also an overheating issue more pronounced in winter when clothing insulation levels were higher (Table 3).

The thermal environment was shown to influence overall comfort in airport terminals (Fig. 5) which is perceived as important only when expectations are not fulfilled (Fig. 15). Despite the regular inconsistency between experienced conditions and comfort requirements, the results suggest high levels of tolerance of the thermal conditions, as demonstrated by the high percentage of comfortable even at the thermal states of TS=±2 (Fig. 5a) as well as from the low percentage of people highlighting thermal conditions as the mostly disliked terminal attribute while experiencing "unacceptable" (i.e. ±2, ±3) thermal sensation (Fig. 15b). Further representative of the thermal tolerance were the winter findings for MAN T1 and MAN T2, where people would still be comfortable with temperatures lower - by 1.2 ºC and 1.9 ºC respectively - than the preferred temperature (Table 4). However, the provision of thermal comfort conditions in airport terminals has been highlighted as a particularly complex challenge due to the different thermal requirements between passengers and staff [18]. An additional consideration comprises the strong dependence of the clothing insulation levels worn indoors on outdoor temperature (Fig. 2) as well as the evidence suggesting that neutral is not the desired thermal state for a considerable fraction of terminal users, which largely reflects the range of activities and therefore of the metabolic rates in the diverse facilities accommodated (Fig. 4).

The 80% acceptability ranges indicated that people can accept on average a temperature range of 6.1 °C in summer and 6.7 °C in winter (Table 4), which is considerably wider than the range recommended by CIBSE for the majority of terminal spaces. Therefore, with the target set at 80% general acceptability, the demonstrated high levels of thermal tolerance alongside the preferred temperatures highlight a potential for energy savings in winter by lowering the heating set-points without compromising thermal comfort conditions. On the contrary, the summer thermal comfort requirements (Table 4) suggest that an increase of the cooling set-points in summer would jeopardise thermal requirements. Accordingly, different approaches to cooling energy savings that do not compromise comfort can be considered. Openings and the periodic use of ceiling fans in certain areas of the terminals can increase air movement which becomes more of an issue at higher temperatures, while the use of more efficient lighting and equipment can reduce internal heat gains. Furthermore, modelling work on the application of phase change materials (PCM) has demonstrated that their use can reduce peak temperatures up to 3°C [36] while they can be also used in accumulation tanks to store chilled water at the desired temperature for later use, thus allowing for the selection of smaller chillers and therefore lower initial investment [37, 38].

In respect to the lighting conditions, the results demonstrated that bright rather than dim conditions were preferred in all terminals (Fig. 12). The consistent preference for more natural light, even in cases where this was deemed to be sufficient (Fig. 10c&d) can have significant implications for the design of terminal buildings and highlights lighting as another field offered for energy savings, by maximising the use of natural light in spaces where security provisions would allow. Interestingly, the findings also indicated that the preference for more daylight peaks in the morning hours, decays later in the day and turns into a preference for "no change" towards the sunset (Fig. 13), suggesting that the desire for natural light follows the endogenous clock associated to the light-dark cycle and the human circadian rhythm.

5. Conclusions

This work investigated the breadth of thermal comfort and lighting conditions in three airport terminals of different capacity and typology. The indoor environment was extensively monitored across the terminal areas where a total of 3,087 people was interviewed for the evaluation of the comfort conditions.

Consistent discrepancies were identified between the preferred thermal conditions and those experienced. Comfort temperatures were found lower than the indoor mean temperature in summer and winter, with the preference for a cooler thermal environment dominating. High levels of tolerance of thermal conditions were demonstrated which alongside the wide acceptability temperature range allow for the reduction of heating energy in winter through the fine-tuning of temperature set-points without compromising thermal comfort. On the other hand, the requirement for further cooling in summer highlights the need to evaluate different airport terminal designs as to enable passive cooling strategies. A strong preference for natural light was also demonstrated, comprising another energy saving prospective through the maximisation of sunlight influx. Ultimately, the findings of this study can inform approaches aimed at improving comfort while different energy conservation strategies are implemented, as well as the regular refurbishments of existing terminal facilities and the design of new terminal buildings.

Acknowledgments

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Appendix: Questionnaire

Date: …………Location in terminal:…….……...Start Time: ……………Gender: ☐ Female ☐ Male

Current Activity: ☐ Seated ☐ Standing ☐ Standing, light activity

SECTION A

Q1. What is the main purpose of your visit to the airport today?

☐ Working here as……………………☐ Travelling to…………………...for ☐leisure or ☐business
☐ Meeter / Greeter ☐ Other…………………….................

Q2. How long have you been in this terminal building?

☐ <15 mins ☐ 15-30 mins ☐ 30-60 mins ☐ >60mins

Q3. What was your activity in the last 15 minutes?

☐ Seated, relaxed ☐ Sedentary activity ☐ Standing, light activity
☐ Standing, medium activity ☐ Walking ☐ Other………………...

Q4. Have you modified your clothing during the past 15 minutes?

☐ Yes, clothes on ☐ Yes, clothes off ☐ No

Q5. Have you consumed any drink in the last 15 minutes?

☐ Yes (☐ Hot drink ☐ Cold drink) ☐ No

SECTION B

Q6. How do you feel at the moment?

☐ Cold ☐ Cool ☐ Slightly Cool ☐ Neither cold nor hot ☐ Slightly warm ☐ Warm ☐ Hot

Q7. How would you prefer to be at the moment?

☐ Much warmer ☐ A bit warmer ☐ No change ☐ A bit cooler ☐ Much cooler

Q8. How would you describe the air movement at the moment?

☐ Very low ☐ Low ☐ Neither low nor high ☐ High ☐ Very high

Q9. Would you prefer the air movement to be:

☐ Much more ☐ A bit more ☐ No change ☐ A bit less ☐ Much less

Q10. What do you think of the air at the moment?

☐ Stuffy ☐ A bit stuffy ☐ Neither stuffy nor fresh ☐ A bit fresh ☐ Fresh

Q11. How do you find the humidity conditions inside this terminal?

☐ Damp ☐ Neither damp nor dry ☐ Dry

SECTION C

Q12. How would you describe the overall lighting environment at the moment?

☐ Very bright ☐ Bright ☐ Slightly bright ☐ Neither bright nor dim ☐ Slightly dim ☐ Dim ☐ Very dim

Q13. Would you prefer it to be:

☐ Much dimmer ☐ A bit dimmer ☐ No change ☐ A bit brighter ☐ Much brighter

Q14. What do you think about the daylight at the moment?

☐ Very little ☐ Little ☐ Sufficient ☐ Much ☐ Very much

Q15. Would you prefer the daylight to be:

☐ Less ☐ No change ☐ More

Q16. Have you experienced discomfort due to glare during your stay in this terminal?

☐ Yes ☐ No

Q17. Overall, do you find the light well distributed?
☐ Yes ☐ No

Q18. How would you rate your overall comfort in this terminal at the moment?
☐ Comfortable ☐ Uncomfortable

Q19. Which one do you consider the most important factor in this building?
☐ Air temperature ☐ Humidity ☐ Air movement ☐ Air freshness ☐ Daylight

Q20. What do you like the most in this space?
…………………………………………………………………………………………………….........

Q21. What you do not like the most in this space?
…………………………………………………………………………………………………….........

SECTION D (only for airport employees)

Q22. Are you working full or part-time?
☐ Full-time ☐ Part-time

Q23. How long have you been working at this terminal? …....years …….months

Q24. Have you noticed any environmental condition problems in this terminal?
☐ Thermally related…………………..……..☐ Visually related…………………………
☐ Other…………………………………...☐ Nothing

Q25. Do you have any control over your thermal and visual environment?
☐ No ☐ Yes (What kind of control?...)

Q26. How would you describe this control?
☐ Satisfactory ☐ Neither satisfactory nor unsatisfactory ☐ Unsatisfactory

Q27. How would you rate the clothing policy in maintaining your thermal comfort?
☐ Flexible ☐ Neither flexible nor inflexible ☐ Inflexible

Q28. How would you describe the effect of the environmental conditions on your productivity?
☐ Negative (why?.................................) ☐ Neither negative nor positive ☐ Positive

SECTION E

Q29. What is your age group? ☐ <18 ☐18-24 ☐25-34 ☐35-44 ☐45-54 ☐55-64 ☐ >65

Q30. Do you live in the Greater Manchester area, Lancashire?
☐ Yes ☐ No (Where do you live?...)

Q31. Have you always lived in this area?
☐ Yes ☐ No (Where are you from?...)

Q32. What is your educational level? ☐ Primary ☐ Secondary ☐ College ☐ University

Q33. Are you a: ☐ In employment ☐ Pensioner ☐ Housekeeper ☐ Student ☐ Other……

CLOTHING
Trousers / Skirt / Dress: ☐ short(s) ☐ long / ☐ light ☐ normal ☐ thick
Shirts/blouses: ☐ T-shirt ☐ Short sleeves ☐ Long sleeves – light, Long sleeves – thick
Sweater / Jacket / Coat : ☐ short ☐ long / ☐ thin ☐ normal ☐ thick
Footwear: ☐ Closed ☐ Open ☐ Boots

End Time:……………