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Shahzad, S. orcid.org/0000-0003-2425-776X, Calautit, J.K., Hughes, B.R. et al. (2 more authors) (2019) Patterns of thermal preference and visual thermal landscaping model in the workplace. Applied Energy, 255. ISSN 0306-2619

https://doi.org/10.1016/j.apenergy.2019.113674

Patterns of Thermal Preference and Visual Thermal Landscaping Model in the Workplace

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Abstract

The main purpose of research on occupant behaviour is to enhance building energy performance. However, it is difficult to reduce the energy use without understanding the occupant, their needs and preferences. Individual differences and preferences for the thermal environment in relation to the spatial context are overlooked in the main stream of research. This study investigates the patterns of occupant thermal preference based on individual differences in perceiving the thermal environment to enhance user comfort and energy performance. A novel method of Visual Thermal Landscaping is used, which is a qualitative method to analyse occupant comfort and user behaviour according to the spatial context. This method drives away from the notion of 'thermal neutrality' and generic results, rather it opens to details and meaning through a qualitative analysis of personal-comfort, based on individual differences and spatial context information. Field test studies of thermal comfort were applied in five office buildings in the UK, Sweden and Japan with overall 2,313 data sets. The primary contribution of the study was the recognition of four patterns of thermal preference, including consistent directional preference; fluctuating preference; high tolerance and sensitive to thermal changes; and high tolerance and not-sensitive to thermal changes. The results were further examined in a longitudinal field test study of thermal comfort. In several cases, occupant thermal comfort and preferences were observed to be influenced by the impact of outdoor conditions, when the windows were fixed. Practical solutions for research, practice and building design were recommended with direct implications on occupant comfort and energy use.

Keywords: Visual Thermal Landscaping (VTL), thermal preference patterns, individual differences in perceiving the thermal environment, user behaviour, energy

1. Introduction

In the developed countries, up to 50% of the energy consumption in the building is due to heating, ventilation and air-conditioning [1]. Janda [2] states that 'buildings don't use energy; people do'. Buildings with poor thermal management suffer from low user satisfaction and high energy consumption [3]. Lack of occupant control in the building can result in an increase in the energy use [4]. User behaviour regarding the thermal environment is the focus of many studies, such as the work of Page et al. [5], Stazi and Naspi [6], Meier et al. [7], Rijal et al. [8], and Stevenson and Leaman [9]. This is particularly relevant in reducing the energy consumption of the building, as demonstrated in the work of Hong et al. [10], Gaetani et al. [11], Sun and Hong [12], Schakib-Ekbatan et al. [13], and Gandhi and Brager [14]. Despite the research on user behaviour, the role of occupant behaviour in energy use of the building is considered as vague, confusing and inconsistent [15]. This unpredictability of user behaviour also creates difficulties in building performance simulations [16, 17]. The main focus of the research in the field remains on the impact of the user behaviour on building performance [9, 18], energy use of the building [19-25], simulating building performance [26-29] or patterns of use of thermal control systems [30], such as window opening [31-37]. Although research suggests significant individual differences in perceiving the thermal environment [38], this observation is not reflected in the main stream of the research, such as the modelling processes of thermal comfort and human behaviour [39]. Most studies focus on the effect and the reaction of occupants (e.g. opening a window), rather than the cause of this behaviour, such as their preference. In order to reduce the energy consumption of the building as well as to improve occupant comfort, it is essential to expand our understanding of the occupants and their requirements in depth, such as occupants' preferences and individual differences in perceiving the thermal environment. Although these two aspects are acknowledged in the field, they are still overlooked in the main stream of the research.

A review by Wang et al. [40] highlights the uncertainty and disagreement of findings and methods on the limited studies in this field. Rather than showing the extent of the studies on individual difference, this review rather shows lack of research, as majority of the studies are concentrated on differences in age, gender and metabolic rate. Although these differences are part of individual differences, they are not the full picture, as they can be considered as differences between different sex groups or age groups, rather than differences between individuals. It is important to acknowledge that respondents from the same age, gender with similar metabolic rate may have different perceptions and preferences for the thermal environment. This matter becomes more important, when sharing the thermal environment, such as in the workplace. For example, two female subjects with similar age and metabolic rate seated close by may have different preferences for the thermal environment. Individual differences are the key subject in research on Personal Comfort Systems (PCS); however, their main purpose is often in providing a solution rather than understanding individual differences. Also, thermal preference is not consistently used in these studies. For instance, Daum etl al. do not include thermal preference in their study. Overall, patterns of user preference regarding the thermal environment have been overlooked in research.

In order to address this gap in the literature, this study investigates the patterns of thermal preference of the occupants based on individual differences in perceiving the thermal environment and the spatial context information. Field test studies of thermal comfort were applied in four office buildings in the UK, Sweden and Japan with an overall sample size of 2,193. About thirty occupants in each British and Swedish buildings participated in the study with a balance of age and gender. Each participant responded to the thermal comfort questionnaire three times a day, including morning, noon and afternoon, while recordings of the thermal environment were applied. A novel method of Visual Thermal Landscaping (VTL) was applied in analysing the collected data in a qualitative way according to the meaning and spatial context. VTL provides a platform to analyse the data on an individual basis in detail and the ability to compare different individuals within the context (e.g. according to the seating arrangements, close proximity to thermal control opportunities). The results of the VTL were compared and further examined in a longitudinal field test study of three office buildings in Japan with overall 2,313 collected data sets. Each respondent filled in a comfort survey questionnaire up to 664 times throughout the year, while environmental measurements were recorded. The results were analysed using statistical methods.

Thermal preference and user behaviour

Duffy [41] criticises that the design of the workplace is disconnected from the user, as it has 'little to do with what the man at his desk really needs'. When individuals experience discomfort, they 'react in ways which tend to restore their comfort' [42]. Hong et al. [16] considers the role of occupant behaviour in the life cycle of the building, as either underestimated or overestimated. This is because it is 'not well understood and oversimplified, due to its stochastic, diverse, complex, and interdisciplinary nature' [16]. There is a gap between research and practice in thermal comfort regarding individual differences.

Researchers tend to average out comfort responses rather than focusing on individuals, while individual satisfaction is low at their workstation in practice [43].

Limited studies examined thermal preference of the respondents, mainly as part of thermoregulatory response using experiments. Jacquote et al. [44] applied an experimental study on healthy women exposing them to ambient temperatures gradually increasing and decreasing between 24°C and 32°C. They found two categories of preferences in the subjects, including narrow ambient temperature range preference and broad ambient temperature range preference. They only found one individual as cool-preference and no subjects as warm-preference. In a clinical experimental study, Luck and Wakeling [45] observed warm preference among some respondents. Stazi and Naspi [6] categorise the triggers' of user behaviour into objective and subjective aspects. The objective aspect includes environmental (e.g. solar radiation, indoor temperature, wind speed, and rain), time related (e.g. entering, leaving, feeding time, and sleeping time) and context related matters (e.g. building type, room exposure, controls accessibility, and interior design). The subjective aspect includes physiological (e.g. age, gender and acclimatisation), psychological (e.g. expectation, habituation and attitude) and social aspects (e.g. group effect, income and lifestyle) [6]. User behaviour is influenced by the availability of thermal control systems, such as windows [35, 46] and they interact with them, as they impact their comfort level [47]. However, the use of thermal control in an open plan office is complicated, due to physical barriers (e.g. close proximity to control systems like a thermostat or the perimeter of the building, where the windows, blinds etc are located) [48] and social barriers (e.g. the impact of 'others') [49].

Individual differences in perceiving the thermal environment and personal comfort systems

Shahzad [49] demonstrates individual differences in perceiving the thermal environment, differences in individual preferences and the dynamic aspect of thermal comfort indicating that occupants keep changing their mind [50]. Heaney et al. [51] found gender differences in thermoregulatory responses in a heat tolerance exposure (between 43.3°C and 60°C) experiment among US navy men and women. They found no significant core temperature differences between male and female subjects, while the skin temperature changes as well as sweating rate were significantly different. Hwang and Chen [52] studied behaviour and thermal adaptation of elderly in residential buildings. They found window-opening in summer and clothing adaptation in winter as the main thermal behaviour. Herkel et al. [53] investigated the seasonal impact on user behaviour. Nagashima et al. [54] applies an experimental study on women regarding the Japanese 'cold Syndrome' or hi-e-sho, related to women experiencing unusual coldness in everyday life. They exposed the female subjects to 'normal' and cooler than normal thermal environments, while measuring the subjects' body core (rectal) and skin temperature as well as applying a comfort survey. They found high sensitivity of a group of female subjects when exposed to mild-cold environments. They found lower metabolic rate but no significant core or skin temperature differences between the comfortable and uncomfortable groups regarding the mild-cold exposure [54]. Although individual differences in perceiving the thermal environment are vaguely acknowledged, still research focuses on temperatures that satisfy all [55] and in practice, there is an attempt to provide a uniform thermal environment [50].

Studies on PCS are practical responses to individual differences, as their main aim is to personalise comfort rather than providing a uniform thermal environment. Studies show that personal comfort systems improve user comfort, while they have the potential to save energy [56], particularly when an HVAC system is in operation [43, 57-60]. Several studies investigate personalised HVAC systems using computers controls, mobile devices and apps [61, 62]. Erickson and Cerpa [62] used occupants as sensors to predict human comfort to reduce the energy use of the building. They used Predicted Mean Vote (PMV) model and thermal sensation on an App to assess thermal comfort. However, when individual differences in comfort temperature was detected, they 'tallied and aggregated' the votes, rather than personalising comfort. Most studies related to personalised comfort are mainly based on thermal sensation vote (TSV) of respondents and do not include thermal preference (TP), such as the work of Daum etl al. [63], and Feldmeier and Paradiso [57]. The latter, developed a heating, ventilation and air conditioning (HVAC) system, which responds to occupant's immediate needs using a wearable device [57]. However, they only used thermal sensation to assess thermal comfort. Zhao et al. [43] criticised the current modelling approaches for human comfort, as they tend to average thermal comfort in both environmental assessment and human response, rather than investigating individual differences. They explain 'personalised thermal preference' as part of their work; however, their study is based on thermal sensation, while thermal preference of the individuals seem to have been excluded from their study. On the contrary, Gao and Keshav [64] Predicted Personal Vote (PPV) model to individualise thermal comfort based on thermal preference of the occupants. Lee et al. [65] introduced the Personalised Preference Model, which is mainly based on the three point thermal preference scale, environmental factors (i.e. air temperature, relative humidity, air velocity, and mean radiant temperature) and personal factors (i.e. metabolic rate and clothing insulation). In this study, there is hardly the mention of thermal sensation vote, it was not recorded nor used. Schweier et al. [39] connected the personality traits to user behaviour and individual's perception of thermal comfort. They found significant relationships between personality traits with thermal sensation and thermal preference of the respondents. Further interdisciplinary research on thermal comfort and psychology shows that thermal control and the feel of control have a great impact on the thermal comfort status of the occupant [66]. Kim et al. [47] investigated users' preferences through a longitudinal field study of using PCS in the workplace. Shahzad et al. [67-69] investigated the impact of PCS on the thermal comfort and preference of individual occupants through field studies of thermal comfort. They recorded occupants' views before and after using the PCS at their work station. They found that the preference and decision making of the occupants are dynamic, as they change throughout the day. They also found that after the respondents were presented with PCS, their preference changed [69].

Energy and user behaviour

Comfort temperature directly influences occupant comfort and building energy use. Currently, buildings are responsible for 40% of the energy use and 36% of the carbon emission in Europe [70]. Offices are considered the most energy intensive buildings [71] and HVAC is responsible for 50% of the energy use in the buildings [71]. By reducing the room temperature in residential buildings by 1°C, approximately 16 TWh energy can be saved across the UK [72]. The impact of decreasing the room temperature on energy use in offices is greater considering the larger size of the building, larger number of occupants, relatively long occupancy hours (e.g. 08:00 to 18:00), and accordingly heating or cooling requirements. Knowing the energy requirement for heating or cooling the room temperature, careful consideration is required in understanding the needs and the preference of individual users.

Hong et al. [16] state that 'gathering data on human-building interaction is a new horizon for achieving energy efficiency in the building sector'. Increasing personal control over the environment has the potential in decreasing the building energy consumption [73]. Bordass et al. [74] state that 'modern control and energy management systems offer the potential to improve individual comfort and reduce energy consumption at the same time'. Nicol and Stevenson [75] recommend the adoption of adaptive opportunity as part of the design of the buildings as an effective strategy to tackle climate change as well as energy and economic challenges. The relationship between occupants' thermal comfort and outdoor environment in naturally ventilated buildings is reported [76]. The impact of combined indoor and outdoor parameters and to recognise which one has a greater impact on occupants' comfort are still open questions [6]. Outdoor factors are out of occupants' reach, while buildings can provide some degree of thermal control for the occupant [6]. Two categories of occupant behaviour related to energy performance of the building are recognised, including adaptive behaviour [77] and non-adaptive actions (e.g. complaint, using electrical equipment or inaction) [78]. An adaptive behaviour includes changing the environment to suit occupant needs (e.g. opening a window, lowering the blinds) and adapting oneself to the environment (e.g. changing clothing layers) [16]. Although the use of personal comfort systems (e.g. desk fans and heaters) is an 'adaptive operation', they are considered as non-adaptive actions, which increase the electricity use of the building [16]. Behavioural adaptation includes consciously or unconsciously applied actions by the occupant in different levels, including on a personal level (e.g. clothing, metabolic rate and changing the location); technological level (e.g. adjustments of the openings, fans and shading); and cultural level (e.g. adjusting behaviour, clothing etc according to socio-cultural and traditional norms) [79-81]. Overall, individual differences and patterns of preferences are missing from thermal comfort research, while they are essential to improve occupant comfort and to reduce the energy performance of the building. Therefore, this work aims to investigate the matter.

2. Research Methods

This work investigated patterns of thermal preferences of occupants. Field studies of thermal comfort were applied in five office buildings in the UK (i.e. building G), Sweden (i.e. building S) and Japan (i.e. buildings B3, B4 and B9) with an overall sample size of 2,313 data sets, as demonstrated in Table 1. Hong et al. [16] criticised relatively small sample size, which is generally relied on in occupant behaviour studies, which has been addressed in this work through the selection of a relatively large data set and three different contexts. The study has two parts and two different analysis of the data, including a short term and a long term study. The short term study was applied in British and Swedish workplaces in June and July. In this part of the study, the relationship between individual's requirements and the spatial context (i.e. the office layout, other occupants, environmental thermal condition, and the availability of thermal control) were analysed using a novel method of Visual Thermal Landscaping (VTL) model. This is a qualitative method, which provides a platform to analyse the data according to the spatial context and meaning. In order to examine the accuracy of the findings of the short term study, a further longitudinal study was applied in a different context of Japanese workplaces, where 2,193 data sets of individual responses to the thermal environment was recorded throughout the year. The results of the short term study were analysed using statistical methods.

Table 1. Sample size, respondent and building related information

Buildings (Code Number)	Location	Country	Mode	HVAC Control	Window	Number of floors	Investigated floor	Data set
G	Inverness	UK	NV *	Local (Central Heating)	Openable	3	1, 2	79
S	Stockholm	Sweden	HVAC **	Local	Fixed	3	2	41
B3	Tokyo	Japan	HVAC **	Central	Fixed	9	3	232
B4	Yokohama	Japan	MM ***	Local	Openable	2	1, 2	1,087
B9	Tokyo	Japan	HVAC **	Central	Fixed	8	8	874
Overall								**2,313**

* NV is regarding naturally ventilated building with central heating in place during the winter months.

** MM is regarding Mixed Mode buildings, where free running, heating or cooling is applied according to the outdoor temperature changes.

*** HVAC is regarding fully air conditioned buildings.

Short-Term Study and VTL Model

About thirty occupants responded to the comfort survey questionnaire three times a day in each office building in the UK and Sweden in summer. The overall sample size for the short-term study was 120 data sets with a good balance of age and gender (i.e. 54 males and 49 females). Environmental, personal and contextual information were collected to be used in the VTL model. The occupants responded to the comfort survey questionnaire, simultaneously environmental measurements were applied and the spatial context information were recorded. The environmental information included dry bulb temperature, relative humidity, mean radiant temperature, and air velocity. The main instrument for recording the environmental data was PCE-GA 70, which allowed an instant measurement at each workstation. Constant measurement of the thermal environment was also applied using Tinytag plus 2, as described in Table 2.

Table 2. Instrument details

Measurements		Instrument	Resolution	Accuracy	Range
Instant measurements	**Dry bulb temperature**	PCE-GA 70 air quality meter	0.1°C	±0.5°C	5 to 50°C
	Relative humidity	PCE-GA 70 air quality meter	0.1°C	±3 RH	10 to 90% RH
Constant measurements	**Dry bulb temperature**	Tinytag Plus 2 TGP-4500	0.01°C	0.01°C	-25 to +85°C
	Relative humidity	Tinytag Plus 2 TGP-4500	0.3% RH	±3% RH	0 to 100% RH

The personal information included age, gender and occupants' views of the thermal environment. Thermal sensation (TSV), thermal preference (TP), overall comfort (OC), and satisfaction (SA) were collected based on the ASHRAE seven-point scale [82], as presented in Table 3. This section included questions only (i.e. no colours were involved, rather it was a standard thermal comfort questionnaire). Mainly sedentary activities took place and summer clothing (0.5 Clo) were observed. The spatial-context related information was recorded, including the spatial layout, openings, seating arrangements, and work performance information (e.g. number of the teams, the performance of the team related to the spatial layout etc). Coding was applied for the respondents and this was marked on the plan of the building to record the seating arrangements. The data collection was repeated three times a day: morning (i.e. between 09:00 to 12:00), noon (i.e. between 12:00 to 14:00) and afternoon (i.e. between 14:00 to 16:00). The period of data collection was one week in each building in June and July 2012. During the field study in the British office, the outdoor temperature was between 13°C to 17°C. The outdoor temperature at the Swedish office was between 14°C to 22°C. Both buildings were open plan offices. The outdoor measurement was recorded on site and in the shade using Tinytag Plus 2. The British office was naturally ventilated, the bottom windows were manually controlled by the occupants, while the top windows were mechanically controlled through the central system to ensure the quality of indoor air. In the Swedish building, air conditioning was in operation, which was controlled centrally by the facilities manager. Although a degree of adjustment was possible at the workstation level using a remote control, this was not available to the occupants and the facilities manager was required to change the settings. The glazing ratio for both buildings was approximately 50%. There was a good level of insulation and the thermal performance of both buildings complied with ASHRAE 55 (2013).

Table 3. The ASHRAE seven point scales [82]

1	2	3	4	5	6	7
Thermal sensation (TSV)						
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
Thermal preference (TP)						
Much cooler	Cooler	Slightly cooler	No change	Slightly warmer	Warmer	Much warmer
Overall Comfort (OC)						
Very uncomfortable	Uncomfortable	Slightly uncomfortable	Neutral	Slightly comfortable	Comfortable	Very comfortable

Satisfaction (SA)						
Very dissatisfied	Dissatisfied	Slightly dissatisfied	Neutral	Slightly satisfied	Satisfied	Very satisfied

In the first section of this work, the VTL model is used, which is a qualitative analysis tool. In the VTL model, data was mapped on the plan layout using colour coding. This was essentially a tope view of a seated person, as illustrated in Figure 1, in which different data was mapped on it. Five data types were mapped for each participant, including the TSV, TP, OC, SA, and PMV.

- TSV: the colour of the area that the person holds in their arms reflected their thermal sensation
- TP: the colour of the head of the person reflected their thermal preference
- OC: the colour of the arms of the person reflected their overall comfort level
- SA: the colour of the hollow around the person reflected their satisfaction level
- PMV: the colour of the floor of the plan reflected the PMV, which was calculated using the thermal measurements and it was associated with sensation of cold to hot

The choice of colours for the parameters relates to temperature (i.e. TSV, TP and PMV), which is similar to the colours of a thermal image; with the blue for cool and red for warm, as illustrated in Figure 1. The deeper the colour, the stronger the sensation (e.g. dark red for hot, dark blue for cold and dark green for very satisfied). For comfort and satisfaction, orange turning into brown shows a negative feeling (e.g. dissatisfied or uncomfortable); yellow illustrates a neutral comfort or satisfaction level (e.g. neither comfortable nor uncomfortable). In general, green illustrates a good quality. For example, comfortable for OC; satisfied for SA; no change for TP; neutral for TSV; and neutral for PMV. So, when all colours appear as green, agreeable and satisfactory conditions are expected. When colours move away from green and they turn into red, blue or orange, a shift from a comfortable situation is expected and hot, cold, discomfort, or dissatisfaction is expected.

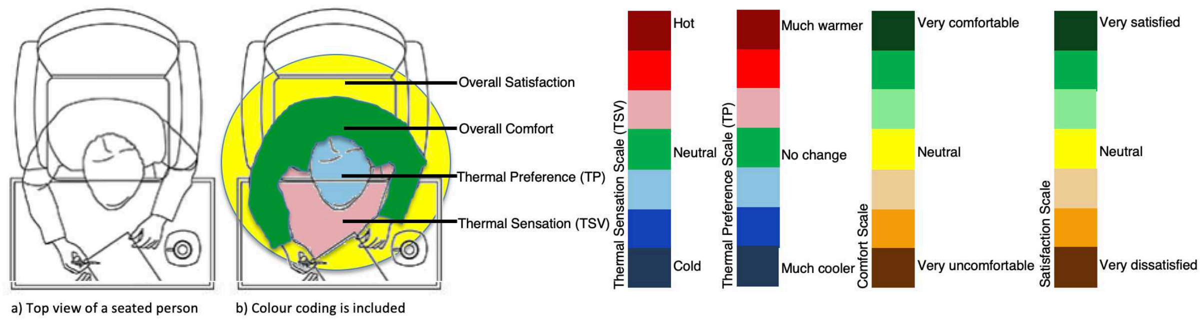

Figure 1. Top view of a seated person and colour coding applied for the VTL model

Figure 2 shows the process of simplifying the graphics involved in the top view of the person. It shows the mapping of the information and the categories, including environmental information based on the thermal measurements and respondents' views based on the survey questionnaire. It also describes an example of how to read the information. In this example, the respondent feels slightly warm (TSV), prefers slightly cooler (TP), while feeling comfortable (OC), but the respondent reported neutral, as their satisfaction (SA) level. Meanwhile the PMV suggests a slightly cool thermal environment (the colour of the background).

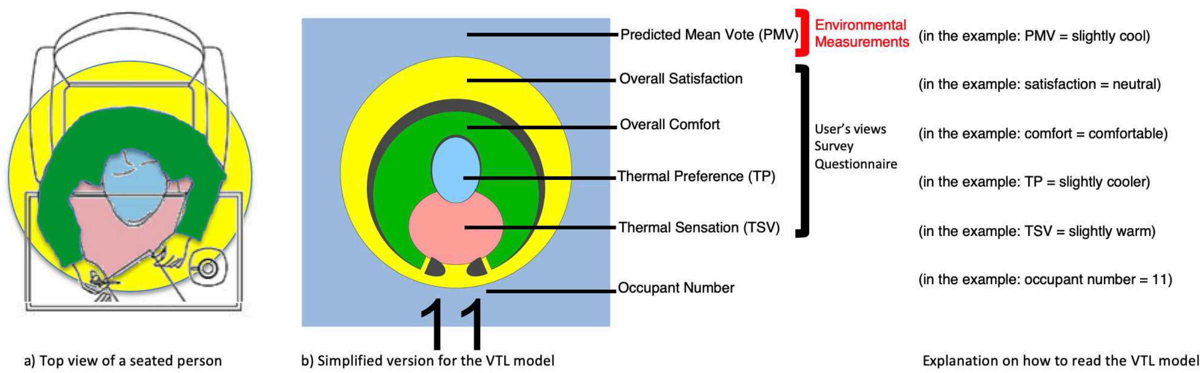

Figure 2. Illustration of how to read the VTL model and the process of simplifying the graphics

Figure 3 is the legend of colour coding to read the information presented as part of the VTL model. Another example is presented at the bottom, where the environment is expected to fell slightly cool (PMV). However, respondent number 11 feels slightly warm (TSV), but prefers not change (TP); and the respondent is very comfortable (OC); but the respondent's satisfaction level is neutral (SA).

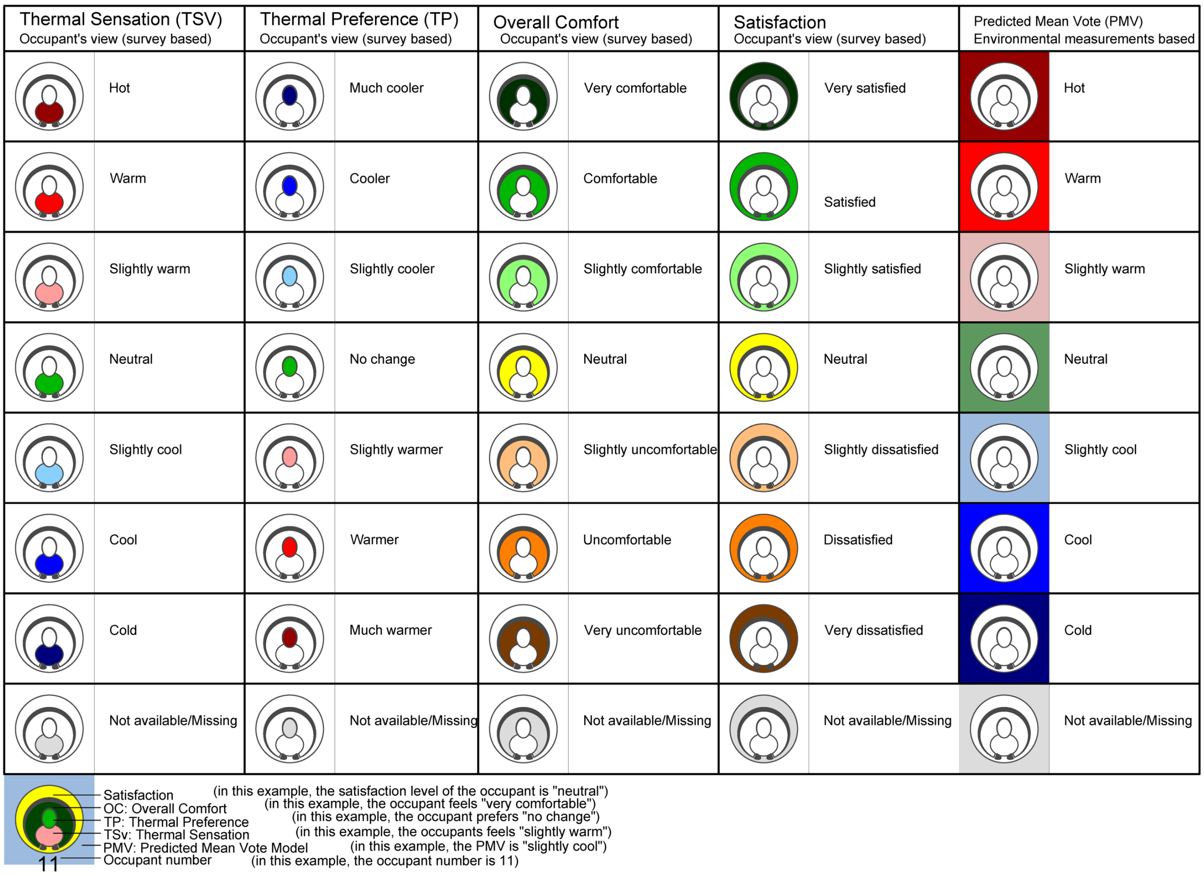

Figure 3. The legend for the use of colour coding for the VTL model

Longitudinal Study

The main analysis tool in thermal comfort is either simulation or mathematical models [83]. Knowing that a non-traditional method was applied in the first section of this work and also considering the difficulty of generalising the results of a qualitative analysis [84], the second section of this work was shaped. A longitudinal study was applied using statistical analysis in order to examine the results of the VTL analysis. Eight respondents in three offices in Japan in 2014 and 2015 participated in this section of the study. Overall 2,193 data sets were recorded, including a thermal comfort survey and environmental data. Each respondent recorded their perception of the thermal environment (TSV, TP and OC) between 50 to 664 times throughout the year from August to October. For TSV, the ASHRAE seven-point scale was applied with some language alterations suited for Japan (i.e. mTSV), as presented in Table 4. The environmental measurements were recorded throughout this period, including indoor temperature (Tg) and outdoor (To) temperature. Further detailed information on the methods and instruments used for the longitudinal study is presented in the work of Rijal et al. [85].

Table 4. Comfort questionnaire applied in the Japanese offices

Number	Thermal Sensation (TSV)	Modified Thermal Sensation (mTSV)	Thermal Preference (TP)
7	Hot	Very hot	
6	Warm	Hot	
5	Slightly warm	Slightly hot	Much cooler
4	Neutral	Neutral	A bit cooler
3	Slightly cool	Slightly cold	No change
2	Cool	Cold	A bit warmer
1	Cold	Very cold	Much warmer

3. Analysis and Results

In the first stage, through using the VTL model, the perception of each individual (i.e. TSV, TP, OC, and SA) was analysed during the day and in comparison to the thermal condition (PMV); accordingly some patterns of preference emerged. In the second stage, occupants within their work and spatial context were investigated, while considering their individual preferences. Accordingly, some suggestions are presented. In the third stage, the energy analysis and the relationship to the patterns of preferences was discussed. In the fourth stage, the recognised patterns are further investigated in the longitudinal field study of the three Japanese offices.

Patterns of Preference

Figure 4 and 5 illustrate the application of the VTL model in the British offices three times a day, including a) morning; b) noon; and c) afternoon. The building envelop and structure are illustrated using a grey colour. Different teams within the office (e.g. finance, advertising etc) are represented with a dashed line and codes, such as G-A and G-B for the British office, as well as S-A and S-B for the Swedish office. The description for the colour coding for the thermal environment assessment (PMV) as well as the individual occupants' perception and preference of the thermal environment (i.e. TSV, TP and OC) were illustrated in Figures 1, 2 and 3.

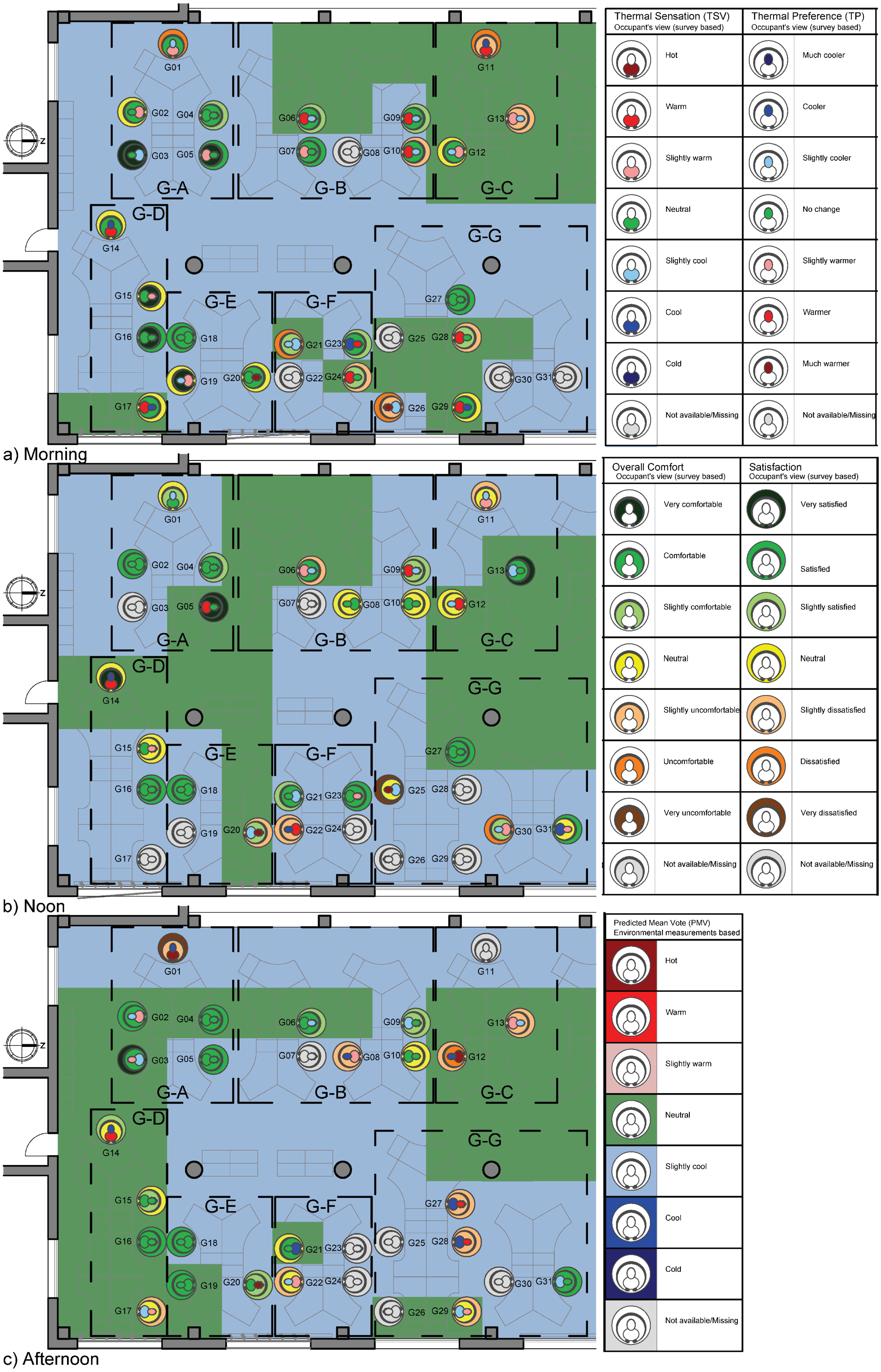

Figure 4. Building G: the office building in Inverness, UK: a) morning; b) noon; c) afternoon

Through comparing the thermal perception of the occupants and their immediate thermal environment throughout the day, the following categories of occupancy were recognised:

- Consistent directional preference
- Fluctuating preference
- High tolerance and sensitive towards thermal changes
- High tolerance and not sensitive towards thermal changes.

Consistent directional preference includes respondents, who have a particular preference towards either warm, cool or neutral conditions. These individuals can also be recognised as warm-preference, cool-preference or neutral-preference. Some of these individuals may change their mind throughout the day, but their preference leans towards a particular direction. For example, occupants with a cool-preference either consistently prefer cooler conditions with the same strength or various strengths (e.g. TP = slightly cooler, cooler or much cooler). For example, occupant G06 (occupant number 06 in the Great Britain office in Figure 4) responded three times in one day to the survey, as all other respondents did. Reading Figure 4, this occupant prefers slightly cooler conditions, regardless of the changes of their TSV during the day, while the PMV remains the same. Occupant G14 consistently feels warm and prefers cooler conditions, although the PMV changes. Therefore, occupants G06 and G14 are observed to have a cool-preference. Some occupants already feel towards cool sensations (e.g. TSV = slightly cool, cool or cold) but either they prefer no change (e.g. occupant S13) or they prefer a slight change, which leans towards cool conditions. For example, occupant G31 in the afternoon has a cool TSV, although his TP is slightly warmer. Overall, his decision is slightly cool, as the degree of change he prefers is not the same strength as his thermal sensation. Some occupants experience slight variations, but their overall preference leans towards cool conditions. For example, occupant G21 in the morning has a slightly cool TSV and his TP is slightly cooler. At noon, still his TSV is slightly cool, but his TP becomes no change; and in the afternoon, his TSV changes to cool, while his TP remains no change. Overall, this occupant is observed to have a cool-preference. The changes of his TSV and TP don't seem to be related to the changes of the thermal environment (PMV). Occupants, who are considered as a cool-preference (consistent directional preference towards cool), include G01, G06, G11, G12, G14, G21, G22, S13, and S14. The following occupants have a consistent directional preference towards neutral conditions: S07, S09, S10, S11, S15, and S17. Occupants with a consistent directional preference towards warm conditions (i.e. warm-preference) include G20, G23, S02, and S03.

Figure 5. Building S: the office building in Stockholm, Sweden: a) morning; b) noon; c) afternoon

Fluctuating preference includes occupants with a changing preference throughout the day with some changes of direction but towards no specific direction. It is observed that the changes of their preference are often not in agreement with the changes of the thermal environment (i.e. PMV). For example, the thermal environment at the workstation of the occupant S12 is assessed as slightly cool (PMV) throughout the day, suggesting a consistent environment. However, in the morning his TSV is cold and he prefers no change (TP); while at noon, his TSV becomes neutral and still he prefers no change (TP). In the afternoon, his TSV changes to slightly cool, and then he prefers slightly warmer (TP) conditions. The comparison between morning and afternoon are particularly interesting, as he is observed happy to feel cold in the morning, while in the afternoon he prefers slightly warmer conditions, when he feels slightly cool. This suggests that his preference changes from cold to neutral, therefore his preference is considered as fluctuating. Occupants G02, G03, G08, G09, G10, G13, G15, G17, G19, G27, G28, G29, G31, S05, S12, and S13 have a fluctuating preference.

High tolerance and not sensitive towards thermal changes include individuals, who don't sense the temperature changes, and they consistently prefer no change (TP) in the thermal conditions. For example, the thermal environment (PMV) of occupant G04 changes from slightly cool in the morning to neutral both at noon and in the afternoon. However, his TSV remains as neutral, suggesting that he is not sensitive towards thermal changes. His TP also remains as no change, suggesting that he has a high tolerance for thermal changes. Therefore, occupant G04 is considered as high tolerant and not sensitive towards thermal changes. Respondents G16, G18, S06, and S16 fall into this category.

The category of high tolerance and sensitive towards thermal changes include occupants who sense the thermal changes, but they consistently prefer no change (TP) in the thermal environment. For example, the thermal environment (PMV) of occupant G05 changes from slightly cool in the morning to neutral at noon and back to slightly cool in the afternoon. His TSV changes from slightly warm in the morning to warm at noon and to neutral in the afternoon. This suggests that he senses (TSV) the change of the thermal environment. However, regardless of the PMV and TSV changes, he consistently prefers (TP) no change in the thermal environment. Therefore, he is considered as having a high tolerance and sensitive to thermal changes. For example, occupants G05 and S04 fall into this category.

Spatial Context

This section analyses the thermal perceptions of the individuals within their spatial context. In the British and Swedish offices presented in Figure 4 and Figure 5, occupants were allocated according to the nature of their job and the teams (e.g. finance, marketing etc) they were part of. The allocation of the occupants was mainly based on knowledge transfer, their work performance, bunding as a team and other work related factors. For example, the employees working in the finance department preferred to sit together to discuss work-related materials with more ease. The same applied to the marketing and other groups. Therefore, occupants did not have the liberty to choose the location of their workstation, due to teamwork, knowledge transfer and other constraints. Although individuals within the group could swap seats or different teams can swap places, it was important for the individuals within a particular team to be seated closely. This seating arrangement was applied by the facilities manager. In the following section, practical suggestions are made based on the VTL observations of the patterns of preference, spatial context and the availability of the thermal control.

In group G-A in building G in the UK (as illustrated with a dashed line in Figure 4), overall the thermal environment (PMV) is assessed as slightly cool and it gradually changes towards neutral in the afternoon. Except occupant G02, no other occupant has access to any means of thermal control in this group. G01 has a consistent directional preference towards cool and he would benefit from PCS with a cooling capacity. Also, in case he swaps seats with G02, he can benefit from accessing the window. G02 and G03 have fluctuating and opposite preferences. It is best for them to sit apart (e.g. G01 can swap seats with G02) and they can both benefit from PCS with both cooling and heating capacities. G04 and G05 both have high tolerance and they are observed as more flexible regarding the seating arrangements.

The group G-B have no access to any means of thermal control, as demonstrated in Figure 4. Although PMV is assessed as slightly cool for most workstations in this group, most of them have a slightly cooler, cooler or no change TP. Since the building is naturally ventilated, the automatic top windows need to be kept open to enhance the ventilation in this location. Alternatively, they can benefit from moving closer to the windows or being provided with PCS with a cooling capacity (e.g. cooled chair or desk fan). Overall, the TP of every occupant in this group has changed throughout the day. Group G-C has a similar situation to G-B with no means of thermal control and all occupants have consistent directional preference towards cool. Therefore, similar solution to G-B is recommended. In group G-D, the thermal environment (PMV) gradually warms up from slightly cool in the morning towards neutral in the afternoon. The occupants in this group are either fluctuating preference or directional preference towards warm; with an exception of G14, who has a directional preference towards cool. Therefore, this group may benefit to be moved away from the windows and their location can be swapped with G-B or G-C. Occupant G14 can benefit from PCS with a cooling capacity.

Overall in G-E group, occupants G20 and G19 have opposite preferences in the morning. Occupant G20 has a consistent directional preference towards warm and she would benefit from PCS with heating capacity and also to be moved away from the window and G19. Occupant G18 has a high tolerance and he is comfortable as it is. In the G-F group, occupants are observed to have different TSV, TP and OC. Their preferences range from cooler to warmer. G21 and G22 have consistent directional preferences towards cool. Although G22 is close to a window, the window is closed, as G20 (sitting behind him) prefers much warmer conditions all day. It is suggested to move G20 with a directional preference towards warm away from the window, so that G22 can benefit from opening the window. It is suggested to move G21 closer to the window, potentially swapping his place with G24. Occupants G20 and G23 have consistent directional preferences towards warm and they would benefit from PCS with heating capacity (e.g. personal heater or thermal chair). In group G-G, most occupants appear to have preferences towards warm conditions, although in some cases opposite preferences are observed. It is suggested to move this group away from the window, particularly those occupants in this group with fluctuating or warmer preferences. Their location can be swapped with G-B or G-C.

In building S in Sweden (as illustrated in Figure 5), although variations in each group and between individuals are observed, occupants do not have access to any means of thermal control. The HVAC system is operating centrally and there are no openable windows. Although the HVAC system was designed in this office to allow individual control of the unit, the management removed individual control. Thus, in case an occupant feels uncomfortable, they need to report to the facilities manager. Because of lack of thermal control and the uniformity of the thermal environment in this office, changes to the allocation of the occupants does not appear to make a difference. However, since the HVAC can perform locally, it is recommended to seat occupants with similar preferences closer and to adjust the thermal environment according to their needs.

Energy Analysis

Balancing energy and comfort is essential, as achieving one end without the other cannot succeed [48]. The analysis of energy and comfort together provides an understanding of the cost of comfort; how much energy is used and accordingly how comfortable the occupants feel. Also, to understand in case the two are aligned, particularly as different ventilation systems are used, including natural ventilation and air conditioning. The British office was totally naturally ventilated with openable windows to allow the occupants to regulate the temperature in the building. This building provided a variety of thermal environments in the building, as the background colours in Figure 4 suggests. The energy performance was calculated based on the information provided by the facilities manager regarding the actual energy readings of the building regarding mainly electricity use and gas. The British office was quite energy efficient (76 kWh/m^2) and it was assessed as excellent by Building Research Establishment Environmental Assessment Method (BREEAM). The Swedish office was a fully air conditioned building with no openable windows, which limited the impact of user behaviour on the building performance. As illustrated in Figure 5, the light blue colour in the background suggests that relatively a uniform thermal environment was provided for all occupants throughout the day. This is aligned with the expectation of a fully air conditioned office building with no openable windows. Regarding the energy performance, the Swedish office had a low energy use (98.6 kWh/m^2). District heating and cooling were provided through a connection to the existing system in the city. The energy consumptions of the two buildings are compared against the Chartered Institute of Building Services Engineering (CIBSE) benchmark [86]. Therefore, both buildings had a relatively low level of energy use, as demonstrated in Figure 6. The energy use of both buildings is lower than all expected benchmarks, including that of the naturally ventilated open plan office and the air conditioned standard office.

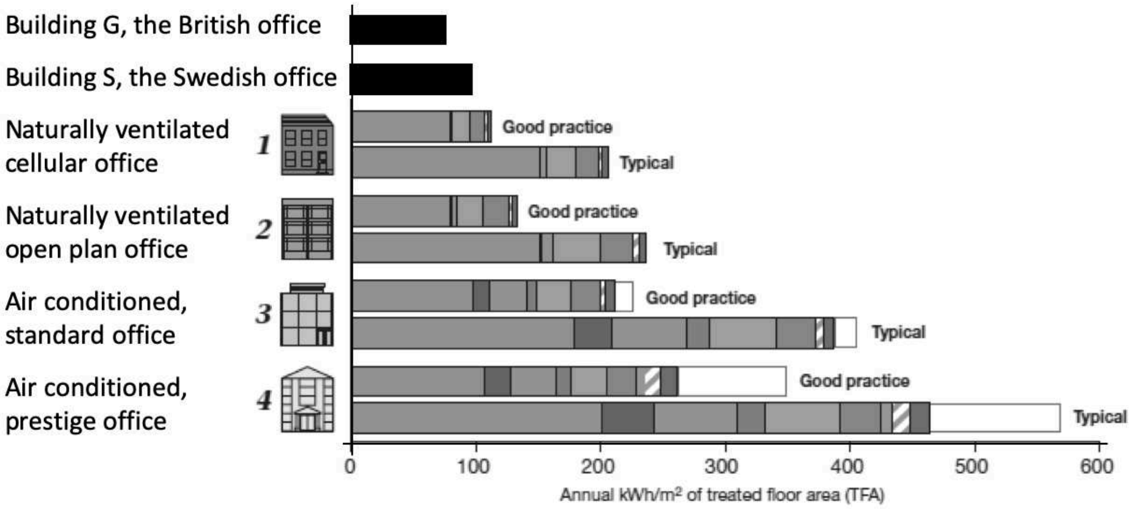

Figure 6. Energy benchmark based on the CIBSE energy use in offices [86]

In order to analyse the relationship between energy and comfort, the quality of the thermal environment and the energy use of the two buildings are compared to occupants' views of comfort. The overall comfort level in the British office was higher than in the Swedish office. Only 9% of the responses were below comfort level in the British office, while this number was much greater (i.e. 24%) in the Swedish office. The PMV was assessed as slightly cool for most of the Swedish office throughout the day. Seventeen responses indicated a preference for warmer conditions at some point in the day. Sixteen responses indicated a preference for no change in the temperature, while four responses indicated a preference for a slightly cooler condition.

Considering that air conditioning was in operation in the Swedish building, energy was used to cool down the air temperature, while a significant number of the occupants preferred slightly warmer to much warmer conditions. The follow up interviews confirmed this, as many respondents, particularly women, explained that they had to put on extra layers when coming to the office in summer, due to the uncomfortably cool room temperatures. Also, a few female subjects explained that due to the cool conditions in the office, they prefer not to wear skirts or dresses. So, extra energy was used with the result of making almost half of the occupants uncomfortably cool. According to Nicol et al. [87], every 1°C change in the air temperature saves about 10% of the energy use of the building. Therefore, by allowing 1°C or 2°C warmer indoor air temperature in the Swedish building in the summer (i.e. not cooling the building too much), between about 10 to 20 kWh/m^2 can be saved, while a significant number of the occupants will potentially feel more comfortable.

The VTL analysis in Figure 5 demonstrates that occupants with different thermal preferences were scattered around the office. Personal differences in perceiving the thermal environment suggests that a simple solution, such as offering a steady and uniform thermal environment to all, is less likely to ensure user comfort. Instead, it is possible to minimise the energy use and to optimise user comfort through localising and preferably personalising comfort by better understanding the needs of the occupants. This is in line with the findings of Brager et al. [46], suggesting that occupants with a high level of thermal control over the windows in summer have a 1.5°C higher neutral temperature, as compared to occupants with no access to any openable windows.

Longitudinal Study Analysis

In the following graphs, 'Neutral' sensation is set as number four, as TSV is based on a seven-point scale. 'No change' TP is considered as number three, as a five-point scale was applied. Table 5 shows the sample description for the longitudinal analysis. Low, high and overall number of data sets are highlighted in red.

Table 5. The description of the sample for the longitudinal analysis

Patterns of Preference	Figure Number	Building	Occupant Number	Gender	Number of Data Sets
Consistent directional preference	Fig.7	B4	S1	F	155
	Fig.8	B4	S9	F	90
	Fig.9	B3	S18	M	57
Fluctuating preference	Fig.10	B9	S5	M	50*
	Fig.11	B4	S12	F	178
High tolerance and sensitive to thermal changes	Fig.12	B9	S1	F	190
	Fig.13	B3	S9	M	175
	Fig.14	B4	S7	M	664*
High tolerance and not sensitive to thermal changes	Fig.15	B9	S9	M	335
	Fig.16	B9	S4	M	299
Overall					**2193***

* Low, high and overall number of data sets are highlighted in red.

Consistent directional preference

The graphs presented in Figures 7, 8 and 9 demonstrate error-bar charts with 95% confidence Interval (CI) limits. They illustrate occupants with a consistent directional preference. The respondent in Figure 7 has a directional preference towards warmer conditions, as when the temperature falls below 20°C, the respondent prefers slightly warmer temperatures. When the temperatures reach above 20°C, the respondent's TSV is neutral and no change is preferred in the temperature.

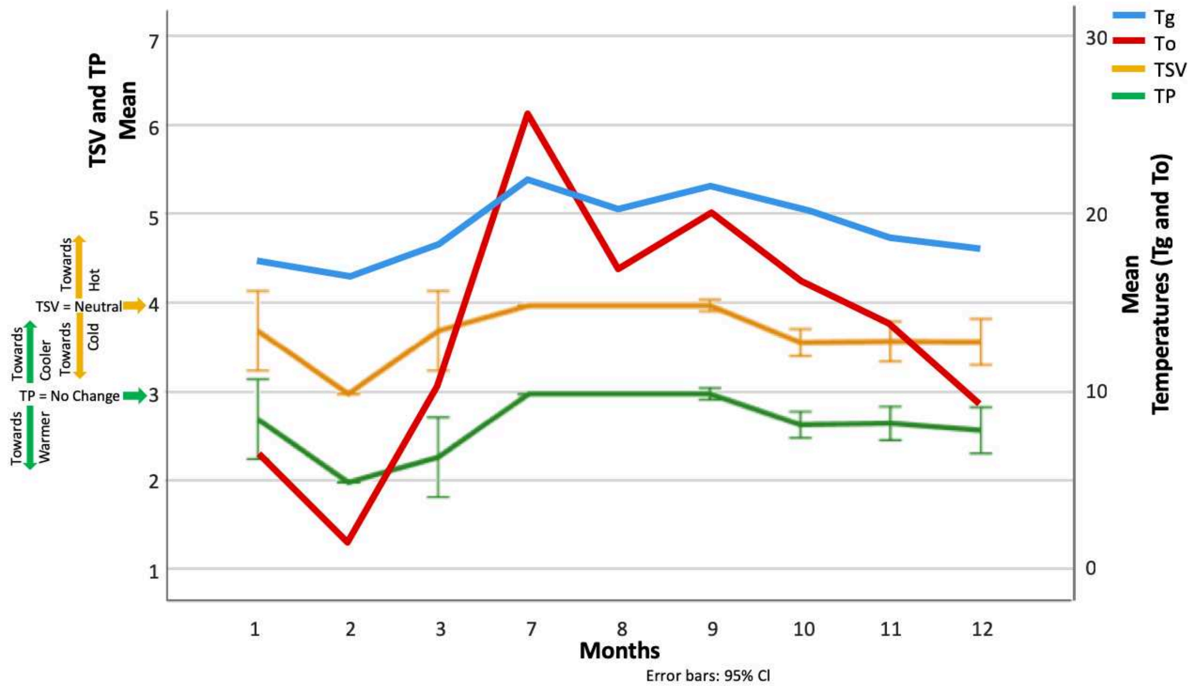

Figure 7. Consistent directional preference towards warmer conditions (Building: B4; respondent: S1; gender: F; data set: 155)

Table 6 demonstrates a significant relationship between TSV, TP, To, and Tg regarding the respondent, who was presented in Figure 7.

Table 6. Correlation between TSV, TP, To, and Tg for the respondent in Figure 7

		TSV	TP	To	Tg
TSV	Pearson Correlation	1	.825**	.310**	.287**
	Sig.		0.000	0.000	0.000
	N	155	155	154	155
TP	Pearson Correlation	.825**	1	.340**	.323**
	Sig.	0.000		0.000	0.000
	N	155	155	154	155
To	Pearson Correlation	.310**	.340**	1	.915**
	Sig.	0.000	0.000		0.000
	N	155	155	154	155
Tg	Pearson Correlation	.287**	.323**	.915**	1
	Sig.	0.000	0.000	0.000	
	N	155	155	154	155

** Correlation is significant at the 0.01 level

In the graphs presented in Figures 8 and 9, the TSV and TP lines and their changes appear quite in agreement with the mid-point toward neutral. Therefore, these two occupants are considered as directional preference towards neutral. Majority of the occupants in the Japanese office (although not demonstrated) fall into this category. In both cases, the outdoor temperature changes are much more pronounce (6°C to 26°C in Figure 8 and 12°C to 28°C in Figure 9). The indoor temperatures in both cases remain within a narrow range between 24°C and 26°C throughout the year. There is hardly any fluctuation in the indoor temperature, suggesting a very good thermal performance in both building B3 and B4. However, the respondent's thermal sensation and preference change quite intensely and they appear to have a stronger relationship with the outdoor temperature. This is specifically visible in months 9, 10 and 11, as the peak in the outdoor temperature changes is more in line with the reflection (TSV and TP) of the occupant. Building B4 is a mixed-mode building with openable windows, which can explain the connection of the occupant to the outdoor conditions. However, Building B3 has a centrally controlled HVAC system with fixed windows. The relationship between the occupant's thermal sensation and preference with the outdoor conditions in this building suggests that the occupant reflects the outdoor conditions regardless of openable windows. Table 7 and Table 8 simply demonstrate a significant relationship between TSV, TP, To, and Tg.

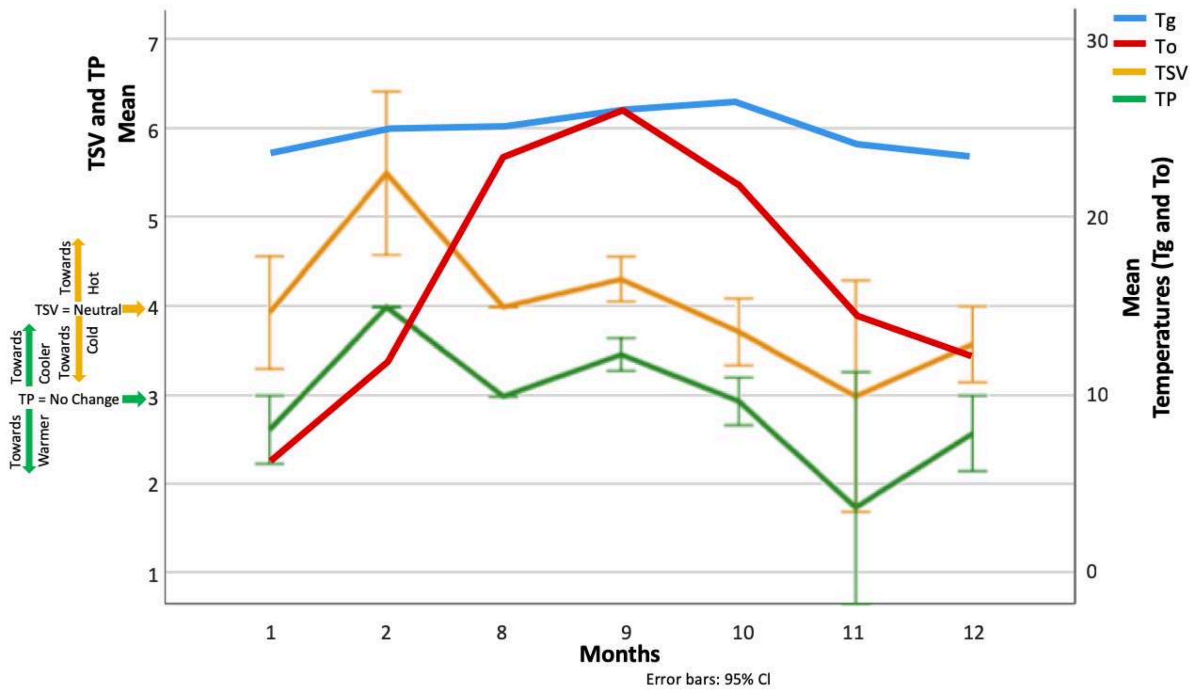

Figure 8. Consistent directional preference towards neutral (Building: B4; respondent: S9; gender: F; data set: 90)

Table 7. Correlation between TSV, TP, To, and Tg for the respondent in

		TSV	TP	To	Tg
TSV	Pearson Correlation	1	.895**	.260**	.511**
	Sig.		0.000	0.038	0.000
	N	64	64	64	64
TP	Pearson Correlation	.895**	1	0.134	.492**
	Sig.	0.000		0.293	0.000
	N	64	64	64	64
To	Pearson Correlation	.260**	0.134	1	.560**
	Sig.	0.038	0.293		0.000
	N	64	64	64	64
Tg	Pearson Correlation	.511**	.492**	.560**	1
	Sig.	0.000	0.000	0.000	
	N	64	64	64	64

** Correlation is significant at the 0.01 level

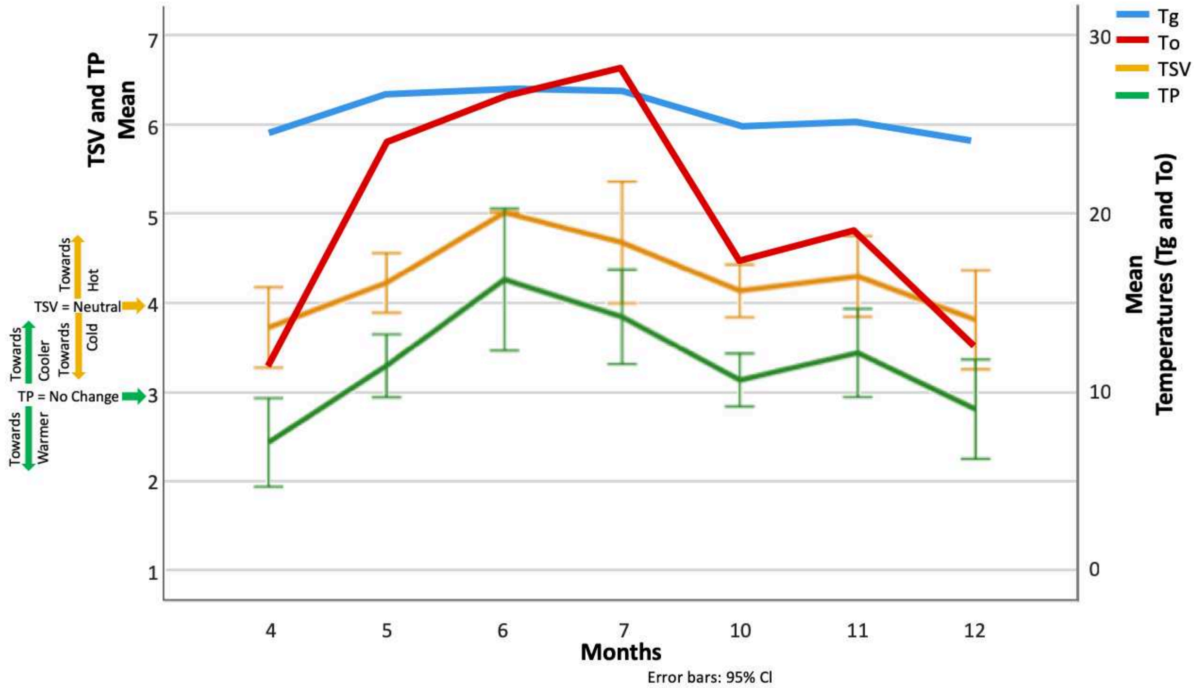

Figure 9. Consistent directional preference towards neutral (Building: B3; respondent: S18; gender: M; data set: 57)

Table 8. Correlation between TSV, TP, To, and Tg for the respondent in Figure 9

		TSV	TP	To	Tg
TSV	Pearson Correlation	1	.857**	.599**	.509**
	Sig.		0.000	0.000	0.000
	N	57	57	57	57
TP	Pearson Correlation	.857**	1	.676**	.616**
	Sig.	0.000		0.000	0.000
	N	57	57	57	57
To	Pearson Correlation	.500**	.676**	1	.890**
	Sig.	0.000	0.000		0.000
	N	57	57	57	57
Tg	Pearson Correlation	.509**	.616**	.890**	1
	Sig.	0.000	0.000	0.000	
	N	57	57	57	57

** Correlation is significant at the 0.01 level

Fluctuating preference

A relatively steady thermal environment despite the outdoor temperature changes is demonstrated in **Error! Reference source not found.**a. The occupant of this workstation appears highly sensitive towards the temperature changes and some confusions are observed in his thermal perception (e.g. in February, March and May). Some confusions are also observed in his thermal preferences, as he appears to have different preferences, when his thermal sensation is slightly warm. For example, in February, he prefers slightly warmer, while in April with relatively similar room temperature and thermal sensation, he prefers slightly cooler conditions. This change in the thermal preference is not in line with any of the factors, including his own thermal sensation, indoor or outdoor temperatures. Therefore, his preference is considered as fluctuating with a high level of sensitivity. Table 9 demonstrates a significant relationship between TSV, TP and Tg. The relationship between TP and To appears stronger than the relationship between TSV and To.

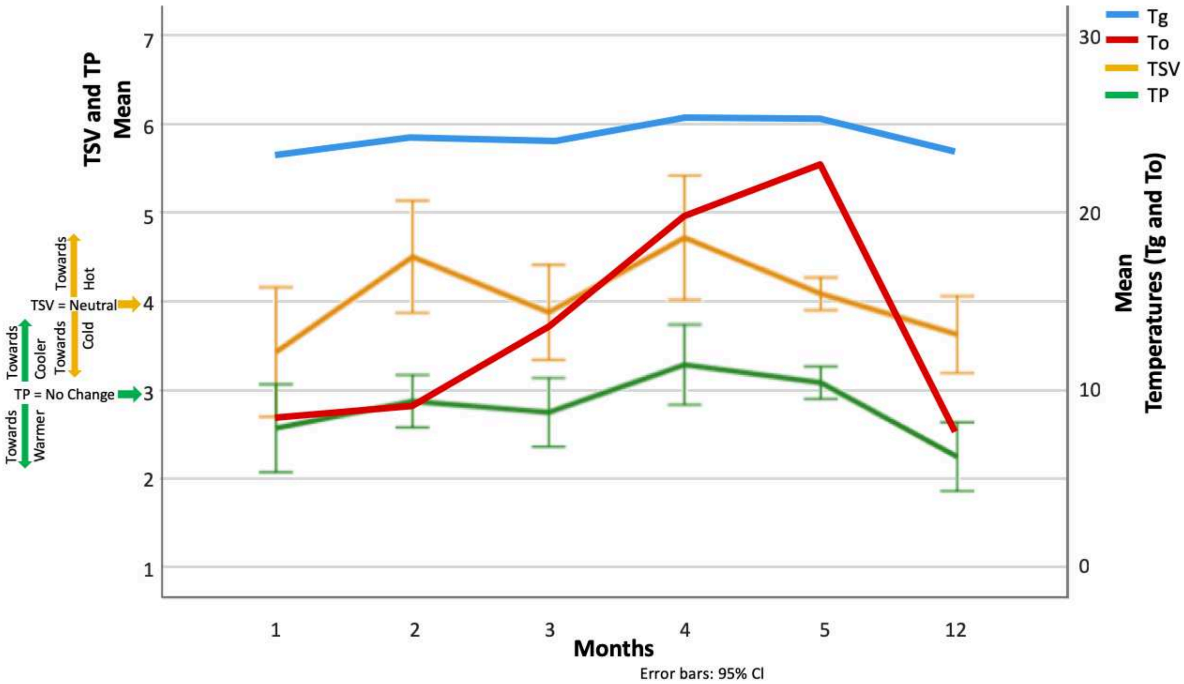

Figure 10. Fluctuating preference (Building: B9; respondent: S5; gender: M; data set: 50)

Table 9. Correlation between TSV, TP, To, and Tg for the respondent in Figure 10

		TSV	TP	To	Tg
TSV	Pearson Correlation	1	.771**	.292*	.552**
	Sig.		0.000	0.039	0.000
	N	50	50	50	50
TP	Pearson Correlation	.771**	1	.506**	.638**
	Sig.	0.000		0.000	0.000
	N	50	50	50	50
To	Pearson Correlation	.292*	.506**	1	.759**
	Sig.	0.039	0.000		0.000
	N	50	50	50	50
Tg	Pearson Correlation	.552**	.638**	.759**	1
	Sig.	0.000	0.000	0.000	
	N	50	50	50	50

** Correlation is significant at the 0.01 level

Figure 11 demonstrates another case of fluctuating preferences. In this case, a neutral TSV seems to be followed by a no change preference (TP). However, as soon as the TSV changes directions away from neutral, the TP changes in the opposite direction. This results in the two lines mirroring each other rather than being aligned. Also, the changes of the TSV is not in line with either indoor or outdoor temperature changes. Some degree of consistency is observed between the changes of the TP and outdoor temperature. Table 10 demonstrates a significant relationship between TSV, TP and Tg. However, no significant relationship was found between TSV and To, while TP appears relevant to To. This confirms the observation of the graph.

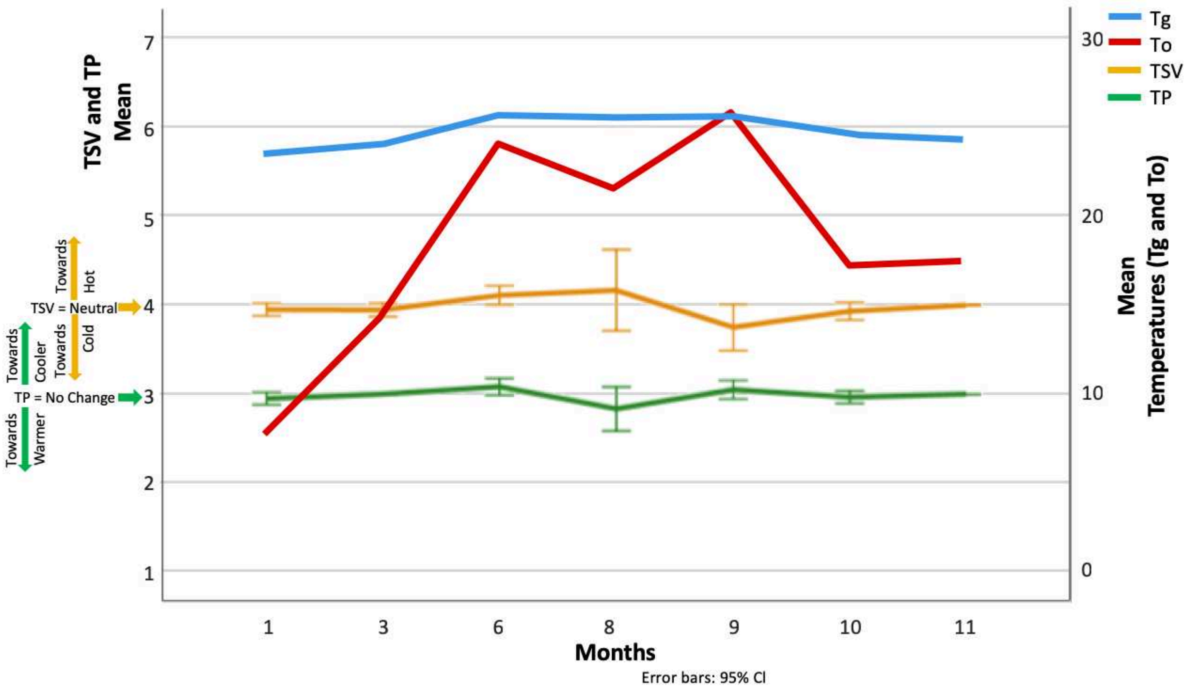

Figure 11. Fluctuating preference (Building: B4; respondent: S12; gender: F; data set: 178)

Table 10. Correlation between TSV, TP, To, and Tg for the respondent in Figure 11

		TSV	TP	To	Tg
TSV	Pearson Correlation	1	.626**	.060	.341**
	Sig.		0.000	0.426	0.000
	N	178	178	177	178
TP	Pearson Correlation	.626**	1	.177*	.340**
	Sig.	0.000		0.019	0.000
	N	178	178	177	178
To	Pearson Correlation	.060	.177*	1	.622**
	Sig.	0.426	0.019		0.000
	N	177	177	177	177
Tg	Pearson Correlation	.341**	.340**	.622**	1
	Sig.	0.000	0.000	0.000	
	N	178	178	177	178

** Correlation is significant at the 0.01 level; and * Correlation is significant at the 0.05 level

High tolerance and sensitive to thermal changes

Figures 12 and 13 demonstrate a relatively steady indoor thermal environment throughout the year (i.e. up to 4°C at each workstation). However, both occupants show quite a high level of thermal sensitivity regarding their TSV. These changes are not quite in line with indoor or outdoor temperature changes. For example, in **Error! Reference source not found.**a in April, when the indoor and outdoor temperatures rise, the respondent feels neutral (TSV). In contrast, in May and June both internal and external temperatures become more steady but still higher than April conditions, while the TSV of the occupant changes to slightly cool. Nevertheless, regardless of the TSV changes, the TP of this occupant remains close to no change showing a high degree of tolerance towards thermal changes. Table 11 demonstrates a significant relationship between TSV with TP and Tg. The relationships between TSV and Tg as well as TP and To do not appear as significant. This confirms the observations of the graph.

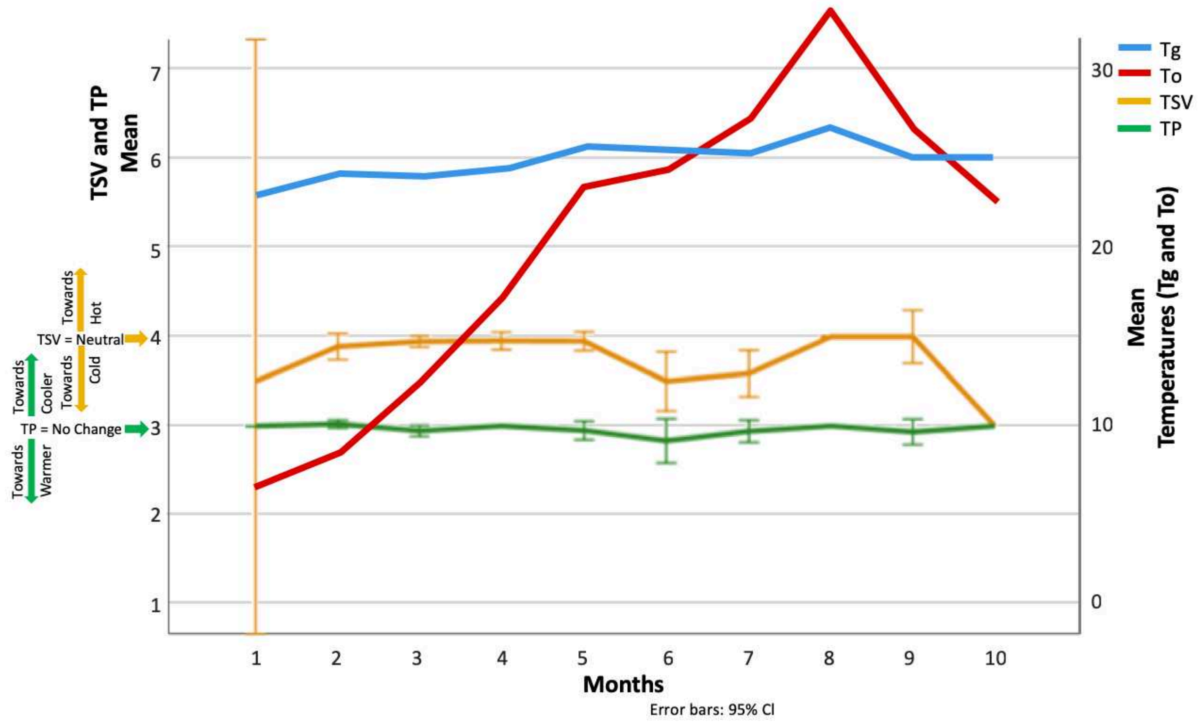

Figure 12. High tolerance and sensitive towards thermal changes (Building: B9; respondent: S1; gender: F; data set: 190)

Table 11. Correlation between TSV, TP, To, and Tg for the respondent in Figure 12

		TSV	TP	To	Tg
TSV	Pearson Correlation	1	.543**	.029	.199**
	Sig.		0.000	0.705	0.008
	N	175	175	175	175
TP	Pearson Correlation	.543**	1	-.159*	.140
	Sig.	0.000		0.035	0.065
	N	175	175	175	175
To	Pearson Correlation	.029	-.159*	1	.618**
	Sig.	0.705	0.035		0.000
	N	175	175	175	175
Tg	Pearson Correlation	.199**	.140	.618**	1
	Sig.	0.008	0.065	0.000	
	N	175	175	175	175

** Correlation is significant at the 0.01 level; and * Correlation is significant at the 0.05 level

The TSV of the participant in Figure 13 seems in line with the internal temperature changes, but its peak is not in line with the external temperature changes. Regardless of the TSV changes, this occupant prefers almost no change throughout the year. Thus, the respondent is considered as high tolerance and sensitive to thermal changes. Table 12 demonstrates a significant relationship between TSV with TP and Tg. The relationships between TSV and To as well as TP and Tg do not appear as significant. This confirms the observation of the graph.

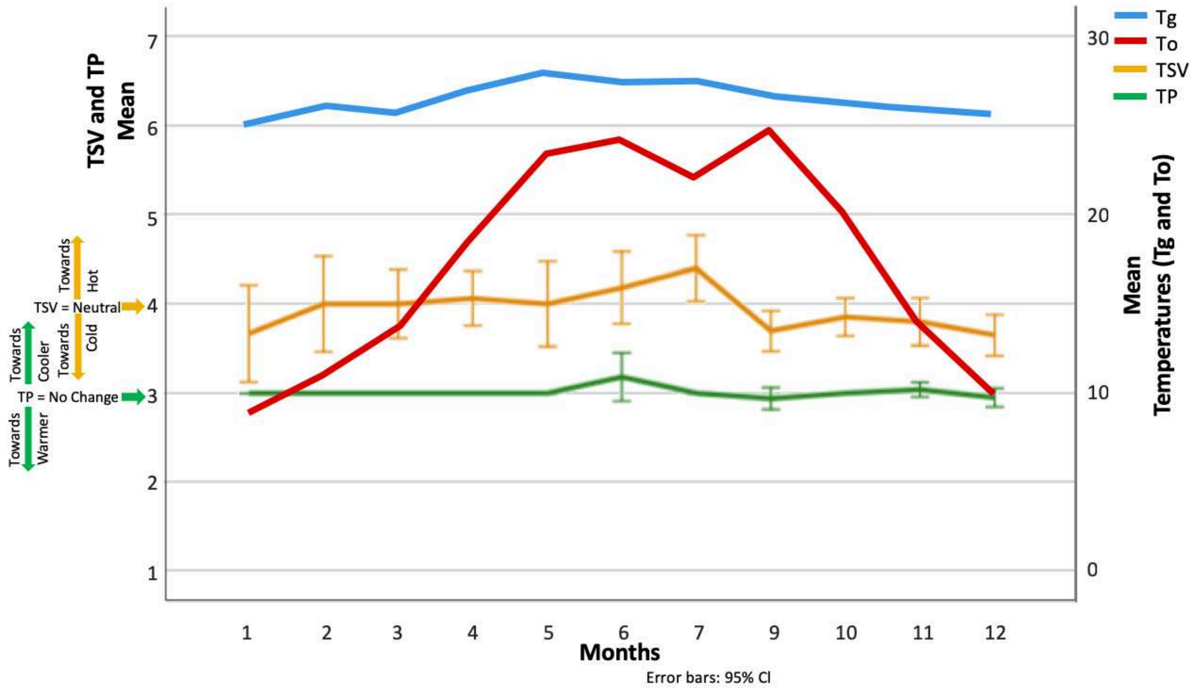

Figure 13. High tolerance and sensitive towards thermal changes (Building: B3; respondent: S9; gender: M; data set: 175)

Table 12. Correlation between TSV, TP, To, and Tg for the respondent in Figure 13

		TSV	TP	To	Tg
TSV	Pearson Correlation	1	.543**	0.029	.199**
	Sig.		0.000	0.705	0.008
	N	175	175	175	175
TP	Pearson Correlation	.543**	1	-.159*	0.140
	Sig.	0.000	0.000	0.035	0.065
	N	175	175	175	175
To	Pearson Correlation	0.029	-.159*	1	.618**
	Sig.	0.705	0.035		0.000
	N	175	175	175	175
Tg	Pearson Correlation	.199**	0.140	.618**	1
	Sig.	0.008	0.065	0.000	
	N	175	175	175	175

** Correlation is significant at the 0.01 level; and * Correlation is significant at the 0.05 level

The TSV of the participant in Figure 14 appears in line with the indoor and outdoor temperatures, particularly regarding the peaks of the temperature changes. Regardless of the TSV changes, this occupant prefers almost no change in thermal conditions throughout the year. Therefore, the respondent is considered as high tolerance and sensitive to thermal changes. Table 13 demonstrates a significant relationship between TSV, TP, To, and Tg.

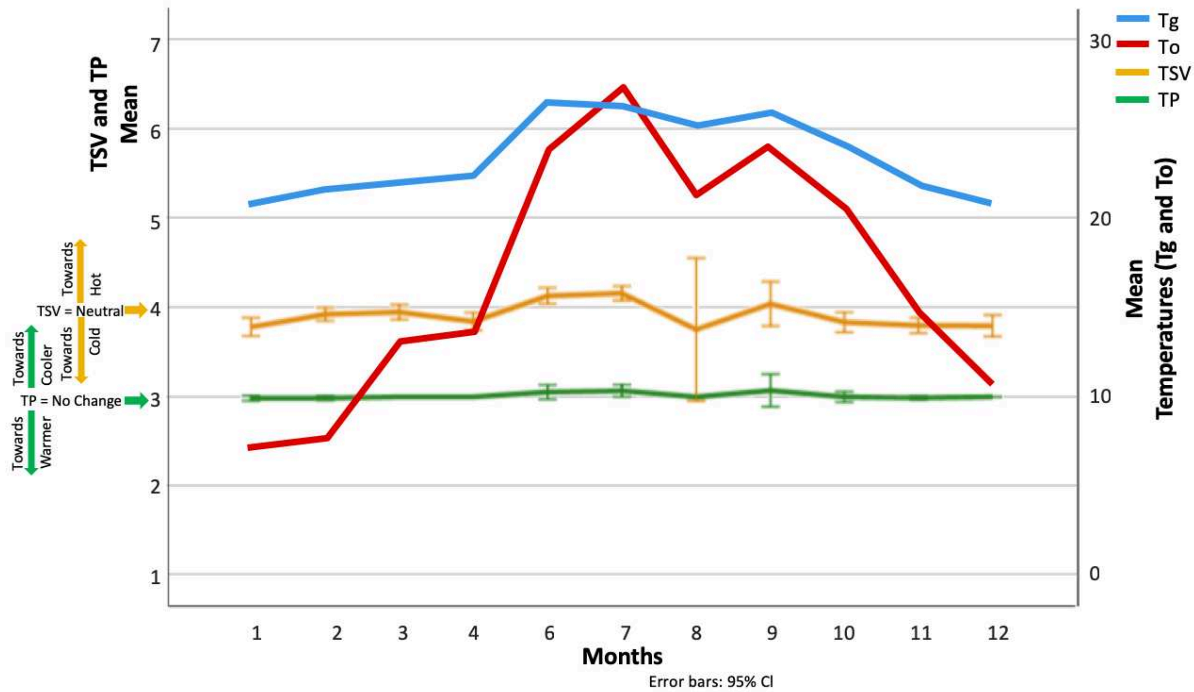

Figure 14. High tolerance and sensitive towards thermal changes (Building: B4; respondent: S7; gender: M; data set: 664)

Table 13. Correlation between TSV, TP, To, and Tg for the respondent in Figure 14

		TSV	TP	To	Tg
TSV	Pearson Correlation	1	.356**	.286**	.324**
	Sig.		0.000	0.000	0.000
	N	664	664	664	664
TP	Pearson Correlation	.356**	1	.150**	.146**
	Sig.	0.000		0.000	0.000
	N	664	664	664	664
To	Pearson Correlation	.286**	.150**	1	.840**
	Sig.	0.000	0.000		0.000
	N	664	664	664	664
Tg	Pearson Correlation	.324**	.146**	.840**	1
	Sig.	0.000	0.000	0.000	
	N	664	664	664	664

** Correlation is significant at the 0.01 level

High tolerance and not sensitive to thermal changes

The graphs presented in Figures 15 and 16 illustrate relatively steady indoor thermal conditions with some changes, despite the significant outdoor temperature changes throughout the year. This uniform performance is expected in building B, where both occupants are located, as this is a centrally controlled HVAC system with fixed windows. The TSV of both occupants remains as neutral and their TP as no change. Although it may seem that the steady indoor thermal environment is the reason for their steady TSV and TP, this was not the case for the respondents in Figures 10, 11 and 13, where the response of the occupants was different despite the steady state of the thermal environment. Therefore, the respondents presented in Figures 15 and 16 are considered as high tolerant individuals with a low level of sensitivity towards thermal changes.

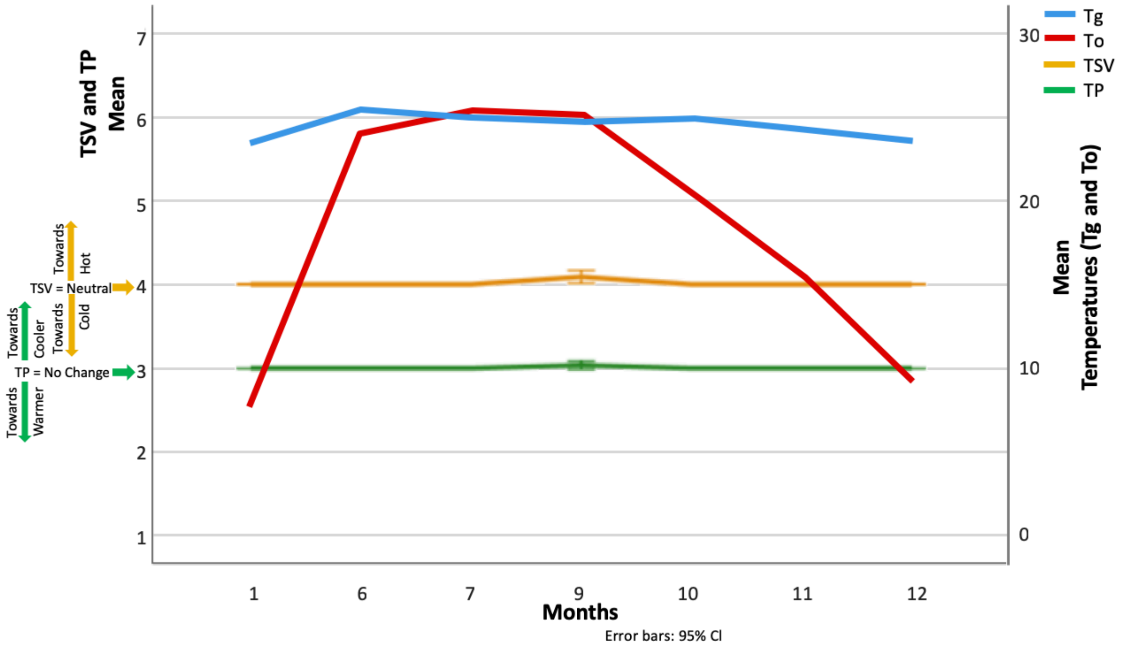

Figure 15. High tolerance and not much sensitive towards thermal changes (Building: B9; respondent: S9; gender: M; data set: 335)

Table 14. Correlation between TSV, TP, To, and Tg for the respondent in Figure 15

		TSV	TP	To	Tg
TSV	Pearson Correlation	1	.630**	.135*	.094
	Sig.		0.000	0.013	0.087
	N	335	335	335	335
TP	Pearson Correlation	.630**	1	.081	.103
	Sig.	0.000		0.141	0.059
	N	335	335	335	335
To	Pearson Correlation	.135*	.081	1	.743**
	Sig.	0.013	0.141		0.000
	N	335	335	335	335
Tg	Pearson Correlation	.094	.103	.743**	1
	Sig.	0.087	0.059	0.000	
	N	335	335	335	335

** Correlation is significant at the 0.01 level; and * Correlation is significant at the 0.05 level

Table 14 demonstrates a significant relationship between TSV, TP, To, and Tg, Table 15 demonstrates a significant relationship between TSV and TP. There is a relationship between TSV and To. However, no significant relationship was found between TP with either To or Tg. This also demonstrates a high level of tolerance of this participant to the thermal environment, as the preference of this respondent does not appear as dependent on the indoor or outdoor temperatures.

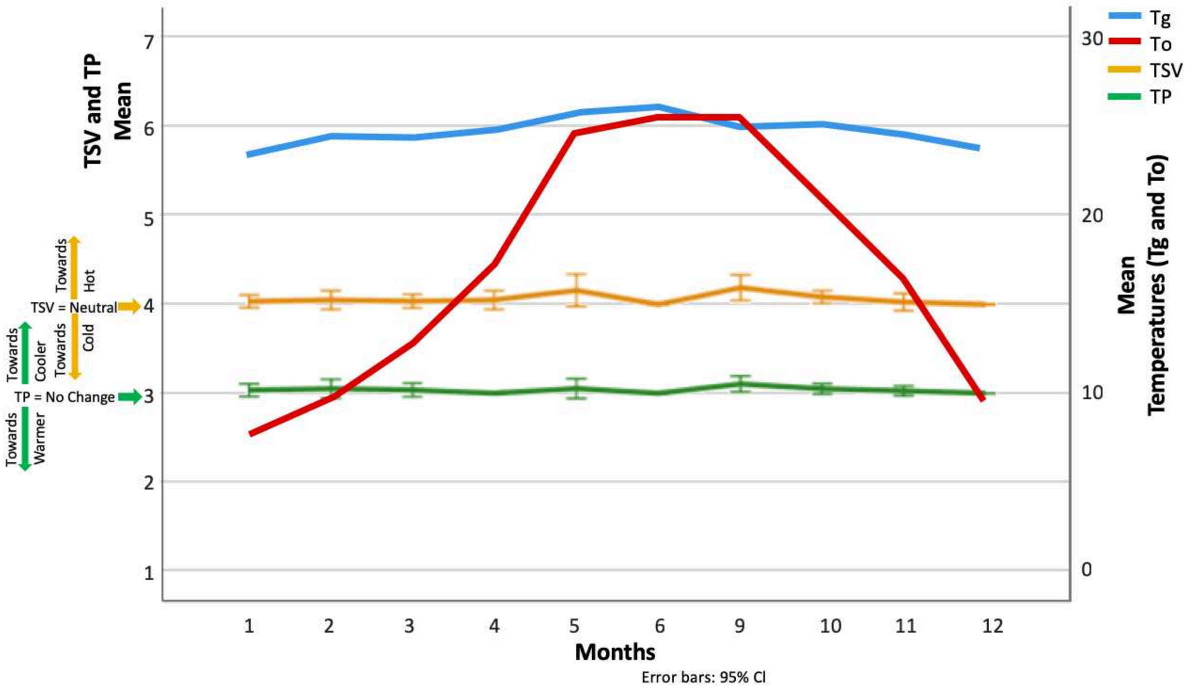

Figure 16. High tolerance and not much sensitive towards thermal changes (Building: B9; respondent: S4; gender: M; data set: 299)

Table 15. Correlation between TSV, TP, To, and Tg for the respondent in Figure 15

		TSV	TP	To	Tg
TSV	Pearson Correlation	1	.720**	.224**	.237**
	Sig.		0.000	0.000	0.000
	N	299	299	297	299
TP	Pearson Correlation	.720**	1	.163**	.216**
	Sig.	0.000		0.005	0.000
	N	299	299	297	299
To	Pearson Correlation	.224**	.163**	1	.640**
	Sig.	0.000	0.005		0.000
	N	297	297	297	297
Tg	Pearson Correlation	.237**	.216**	.640**	1
	Sig.	0.000	0.000	0.000	
	N	299	299	297	299

** Correlation is significant at the 0.01 level

4. Discussion

Individual differences and energy performance

This work was based on individual differences in perceiving the thermal environment. This is in contrast with the common approach in thermal comfort studies, which overlooks the differences between individuals. Limited studies focus on the gender and age differences. Although these works are considered as 'individual differences' [40], they are rather differences in sexual thermal perceptions or age group differences. Only a handful of studies really focus on differences between individuals or try to address them through personalised approached. However, they do not appear consistent in data collection, as some important information is not included in some studies, such as thermal preference and spatial context information. By mentioning individual differences, truly differences among individual occupants need to be considered. For example, two respondents with the same age, gender and with similar size and body mass may have totally different perceptions and preferences regarding the thermal environment. The existence of this matter although vaguely acknowledged in thermal comfort research, but it has been strongly avoided, mainly due to the complexity of the matter. The aim of this work was to investigate the nature of this difference through understanding different patterns through the application of a different approach and by including spatial context information. This is useful to enhance our knowledge of individual occupants in perceiving the thermal environment, their preferences and requirements, which ultimately motivate their behaviour. Expanding our knowledge of users and their behaviour, provides a platform for researchers to investigate new strategies to achieve both occupant comfort and energy efficiency. This knowledge is essential for building designers to better design for the thermal environment and for facilities managers to maintain the thermal environment in practice to respond to individual needs, while keeping the energy demand low. Currently, balancing energy and comfort is a challenge, and most workplaces perform at one end of the spectrum at the expense of the other end [48]. As Janda [2] states, 'buildings don't use energy; people do'. When occupants are uncomfortable, they will react in order to restore their comfort [42]. In case suitable strategies as part of the building design are not provided, this can result in increasing the energy use of the building [4]. Therefore, deeper understanding of thermal requirements of individual occupants is an effective approach to reduce the current and future energy demand of the building.

The results of this study showed that when individual differences are ignored, extra energy can be used, while making occupants uncomfortable. For example, the Swedish case study provided a uniform thermal environment, as it is expected in a fully air conditioned building with no means of occupant control. Therefore, energy is used to cool the building in summer; however, about half of the occupants preferred slightly warmer to much warmer conditions. Therefore, this extra energy was used and it resulted in occupant discomfort. Also, the results indicated that increasing the room temperature in a uniform thermal environment does not necessarily improve thermal comfort conditions, as many occupants preferred no change in the temperature and a few of them preferred cooler conditions. The VTL model showed that the occupants with different preferences are scattered around the office. This complexity indicated that a simple solution of providing a uniform thermal environment does not satisfy individual needs. The British office was a naturally ventilated building, which provided variety of local room temperatures. Also, limited thermal control (e.g. openable windows) was provided for the occupants seated around the perimeter of the building. The British office had a lower energy use and a higher comfort level, as compared to the Swedish building. In order to increase user comfort, the VTL model demonstrated that by recognising individual preferences, it is possible to revisit the seating arrangements to allocate warmer locations to warm preference occupants and vice versa. Also, occupants with a high tolerance were recognised as more flexible with the seating arrangement regarding the thermal environment. Therefore, changing the seating arrangements according to preference patterns, thermal environment, thermal control, understanding the work and other requirements is likely to result in increasing occupant comfort, while maintaining a low energy use.

Many personalised comfort studies investigate air conditioned buildings. However, this study suggests that a naturally ventilated building equipped with occupant control can perform better regarding a lower energy use and higher levels of occupant comfort. An addition of personalised comfort systems in the naturally ventilated office has the potential to enhance user comfort. By using the VTL model and recognising the patterns of preference, not all occupants require personal comfort systems (such as high tolerance individuals); thus, it is possible to minimise the energy use while enhancing user comfort.

VTL and patterns of thermal preference

This work analysed individual occupants throughout the day using the novel qualitative VTL method. This method provides another approach and perspective in understanding occupants and finding patterns through meaning and contextual information, which may not be easy through quantitative methods. One of the difficulties of using a qualitative method is the difficulty of generalising the results. This has been considered in this work through the longitudinal study in a different context and further research is useful to confirm and to generalise the findings of this study. When using the VTL method, after the repetition of the matter (e.g. pattern) was observed and the initial hypothesis was formed, it was easy to test it through a quantitative analysis, as is the case in this work. The use of the VTL method enabled the recognition of the four patterns of preferences, which was the key finding in this study, including consistent directional preference; fluctuating preference; high tolerance and sensitive to thermal changes; and high tolerance and not sensitive to thermal changes.

To the knowledge of the authors, three out of four recognised patterns of preferences (i.e. excluding the consistent directional preference) in this work have not been recognised by other studies. Respondents with different and opposite thermal preferences during the study were recognised as fluctuating preference. In some cases the response of the occupant was not in line with the changes of the thermal environment either. This group has not been recognised in other works and further research is recommended to unfold the reason for the changing preferences in this group. The final two groups are high tolerant respondents, which are divided into sensitive and not sensitive to thermal changes. Some individuals clearly sensed the thermal changes (TSV) and several occupants showed a high degree of sensitivity. However, they preferred (TP) no changes in the thermal environment and they found it acceptable. This suggested a high degree of tolerance for these individuals, while being sensitive to thermal changes. The follow up interviews confirmed this finding. The respondents with high tolerance and not sensitive to thermal changes were exposed to different indoor conditions. However, their TSV did not change and they consistently preferred no change (TP) in thermal conditions. Therefore, this group were recognised as high tolerant and not sensitive to thermal changes.

The consistent directional preference included warm-preference, cool-preference and neutral-preference. Although slight variations were observed, these individuals generally preferred a particular thermal preference. For instance, the preference of some occupants changed between slightly cooler to cooler conditions throughout the day, therefore overall they had a cool-preference. The study also found warm-preference individuals, which is in agreement with the work of Nagashima et al. [54] and their report of the ‘cold syndrome’. However, using the word ‘syndrome’ suggests a negative meaning, rather than individual differences. Also, their work is mainly concerning the sensitivity of the respondent, while this work suggests that the tolerance of the occupant is more important. For example, occupants may be sensitive to the thermal environment but they may find it acceptable, as they prefer no change to the thermal environment. Luck and Wakeling [45] observed warm-preference individuals. In their study they did not find any respondent with cool-preference. The third group in our work had a consistent neutral-preference and by far this was the largest group in both short-term and long-term study. Overall, the recognition of the four preference categories is useful in improving comfort conditions and the use of qualitative methods is recommended to uncover individual differences in perceiving the thermal environment.

5. Conclusion

The key findings of this work were realised through the use of a novel Visual Thermal Landscaping method, which provided a platform for a qualitative analysis of the data according to the spatial context and meaning. This method enabled four patterns of thermal preference for occupants to be recognised, as follows:

- Consistent directional preference
- Fluctuating preference
- High tolerance and sensitive to thermal changes
- High tolerance and not sensitive to thermal changes

In order to successfully research, design, build, and manage the thermal environment, it is essential to understand the occupants, their requirements, patterns of behaviour and their response to the context as part of experiencing the thermal environment. While majority of the research in the field is concerned about occupants' perception of the thermal environment, this study recommends further research on understanding the occupants. The spatial context and work related context are important parts of thermal comfort research in the workplace. Lack of this information results in overly simplifying the matter and to overlook important information on how to improve occupant comfort and energy use of the building. For example, this was demonstrated in the British case study in this work, which was a low energy naturally ventilated building with a variety of thermal environments and the availability of some environmental control. Through understanding the work related relationships and preference patterns, it was possible to suggest changes in the occupancy locations to enhance the occupant comfort, while maintaining the low energy of the building. In contrast, the Swedish building was a fully air conditioned building with no thermal control for the occupants. Although the energy use of the building was relatively low and it provided a uniform thermal environment, there was a low user comfort regarding the thermal environment. Also, due to the uniformity of the thermal environment and the nature of individual differences in preferring different thermal environments, there seemed to be no easy solution to resolve the matter. The extra energy, which was used to cool the building in summer, resulted in discomfort of half the occupants, as they preferred slightly warmer to much warmer thermal environments.

Personal comfort studies are the main stream of the research that works towards individual differences in perceiving the thermal environment. However, majority of this research is focused on a user controlled air conditioning system. This work recommends further studies on naturally ventilated buildings with the availability of personal comfort systems for occupants, who need it. As the two categories of high tolerant individuals may not require a personal system. Also, Visual Thermal Landscaping model can be applied to understand individual occupants and their context to provide practical solutions to enhance user thermal comfort and energy management of the building.

In several cases, the thermal comfort and preference of occupants were influenced by a combined impact of indoor and outdoor conditions. This was regardless of the building being mixed-mode with openable windows or fully air conditioned with fixed windows. Although thermal sensation of the occupants is important, the essential information is whether they prefer any change in the thermal environment or not. This is clearly demonstrated in the category of sensitive individuals towards thermal changes, while they have a high tolerance and prefer no changes. Although they felt the temperature changes (thermal sensation), but they found it acceptable and preferred no change in the thermal environment (thermal preference). Some occupants with a consistent directional preference towards warm or cool reported to have a warm or cool thermal sensation, but they preferred no change. Therefore, changing the thermal environment would result in their discomfort, while extra energy would be required for this change. Understanding patterns of preference and occupants' needs are essential in thermal comfort research and practice, while they directly influence the energy management of the building.

Acknowledgement

The authors acknowledge many contributions, including the University of Edinburgh, the University of Sheffield, the Gotoh Educational Corporation, Hulic, Tokyo City University, Tokyu Fudosan Next Generation Engineering Center, and to all students for data entry. Part of this research was supported by Grant-in-Aid for Scientific Research (C).

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