Does a Neutral Thermal Sensation Determine Thermal Comfort?

Dr Sally Shahzad PhD
Department of Mechanical Engineering and the Built Environment, University of Derby
sally.shahzad@gmail.com

John Brennan
Edinburgh School of Architecture and Landscape Architecture, Edinburgh College of Art, University of Edinburgh

Dr Dimitris Theodossopoulos PhD
Edinburgh School of Architecture and Landscape Architecture, Edinburgh College of Art, University of Edinburgh

Dr John Kaiser Calautit PhD
Department of Architecture and Built Environment, University of Nottingham

Dr Ben Richard Hughes PhD
Department of Mechanical Engineering, University of Sheffield

Abstract

The neutral thermal sensation (neither cold, nor hot) is widely used through the application of the ASHRAE seven-point thermal sensation scale to assess thermal comfort. This study investigated the application of the neutral thermal sensation and it questions the reliability of any study that solely relies on neutral thermal sensation. Although thermal-neutrality has already been questioned, still most thermal comfort studies only use this measure to assess thermal comfort of the occupants. In this study, the connection of the occupant's thermal comfort with thermal-neutrality was investigated in two separate contexts of Norwegian and British offices. Overall, the thermal environment of four office buildings were evaluated and 313 responses (three times a day) to thermal sensation, thermal preference, comfort, and satisfaction were recorded. The results suggested that 36% of the occupants did not want to feel neutral and they considered thermal sensations other than neutral as their comfort condition. Also, in order to feel comfortable, respondents reported wanting to feel different thermal sensations at different times of the day suggesting that occupant desire for thermal comfort conditions may not be as steady as anticipated. This study recommends that other measures are required to assess human thermal comfort, such as thermal preference.

Keywords: Neutral Thermal Sensation, ASHRAE, Thermal Comfort, Workplace

Practical Application

This study questions the application of neutral thermal sensation as the measure of thermal comfort. The findings indicate that occupant may consider other sensations than neutral as comfortable. This finding directly questions the standard comfort zone (e.g. ASHRAE Standard 55) as well as the optimum temperature, as many occupants required different thermal sensations at different times of the day to feel comfortable. These findings suggest that a steady indoor thermal environment does not guarantee thermal comfort and variations in the room temperature, which can be controlled by the occupant, need to be considered as part of the building design.

1. Introduction

Neutral thermal sensation is commonly used as the measure of thermal comfort [1-3], and the ASHRAE seven-point thermal sensation scale (based on thermal-neutrality and presented in

Table 1) is the most widely used measure of thermal comfort [4]. ASHRAE also introduces thermal preference, comfort and satisfaction scales (shown in

Table 1), but most studies only consider thermal sensation in assessing thermal comfort [4] and they are focused on this measure [5,6]. This goes so far as some researchers defining thermal comfort as an ‘intermediate point, when neither cold nor hot’ [7]. Many researchers, such as Fanger, investigated the comfort temperature, in which the occupant feels neutral [3]. These findings directly influenced the creation of standards, such as the thermal comfort zone in thermal comfort standards (e.g. ASHRAE Standard 55 [8]). These standards try to define the thermal conditions, in which over 80% of the occupants are likely to feel neutral and therefore comfortable [9].

Table 1: The ASHRAE seven point scales [2]

Thermal sensation scale						
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
-3	-2	-1	0	1	2	3
Thermal preference scale:						
Much cooler	Cooler	Slightly cooler	No change	Slightly warmer	Warmer	Much warmer
-3	-2	-1	0	1	2	3
Comfort scale:						
Very uncomfortable	Uncomfortable	Slightly uncomfortable	Neutral	Slightly comfortable	Comfortable	Very comfortable
-3	-2	-1	0	1	2	3
Satisfaction scale:						
Very dissatisfied	Dissatisfied	Slightly dissatisfied	Neutral	Slightly satisfied	Satisfied	Very satisfied
-3	-2	-1	0	1	2	3

Other researchers define thermal comfort through thermal neutrality. For example, McCartney and Nicol define the comfort temperature as 'the indoor operative temperature at which an average subject will vote comfortable (or neutral) on the ASHRAE scale' [10]. The ASHRAE Handbook 2009 states that 'acceptability is determined by the percentage of occupants who have responded neutral or satisfied (0, +1, +2, or +3) with their thermal environment' [2]. Although the application of thermal neutral sensation as the measure of thermal comfort has been criticized [11], many studies continue using this measure only. Followed by Humphreys' question: 'Do people want to feel neutral?' [11]. De Dear highlights the fact that using the 'neutral thermal sensation' on the PMV (Predicted Mean Vote) seven-point scale 'says nothing about whether the occupants are actually going to like it' [12]. The combined application of thermal sensation and thermal preference has been suggested [11], however many researchers continue using one measure (thermal sensation) only. The few researchers, who apply thermal preference scale, mainly aim to clarify weather or not the occupant feels neutral, rather than investigating occupants' desire to feel neutral in the first place. In this study, the connection of the occupant's thermal comfort with thermal-neutrality was investigated in two separate contexts of Norwegian and British offices. Overall, the thermal environment of four office buildings were evaluated and 313 responses (three times a day) to the ASHRAE seven point scale thermal sensation, thermal preference, comfort, and satisfaction were recorded.

2. Previous Related Work

Thermal comfort is defined by ASHRAE Standard 55 as ‘that condition of mind that expresses satisfaction with the thermal environment’ [13]. In this definition, satisfaction and condition of mind are the indicators of thermal comfort and there is no mention of thermal neutrality. However, the ASHRAE Handbook considers neutral thermal sensation as the measure of thermal comfort, it even goes further and in several cases uses ‘thermal neutrality’ instead of thermal comfort [2]. Fanger’s PMV model is all based on the neutral thermal sensation [3]. The PMV model is widely used by researchers to assess the thermal environment and the thermal performance of a building in field test, experiments and simulation studies. Fanger states that ‘it is especially the relationship around the neutral point which is of interest’ [3]. Hawkes defines thermal comfort as the ‘intermediate point, when neither cold nor hot’ [7], which shows thermal neutrality. Van Marken and Kingma state that ‘thermoneutral zone (TNZ) is defined by physiologists as the range of ambient temperature at which temperature regulation is achieved only by control of sensible (convective and radiative) heat loss, i.e. without regulatory changes in metabolic heat production (facultative thermogenesis) or evaporative heat loss (sweating)’ [14]. Fanger introduced the steady state theory based on the balance of the temperature between human body and the thermal environment [3]. It suggests that in case any of the two is warmer, it will release the extra heat to the other to reach the steady state [15,16], which will minimise the person’s energy gain or loss [17]. In other words, in order to achieve a sustainable thermal balance between human body and the surrounding thermal environment, the produced heat should be in equilibrium with the transmitted heat [15].

The ASHRAE seven-point scale is criticized, as it is ‘thermal sensation only and not thermal comfort’ [18]. Some researchers reported users’ preference for non-neutral thermal sensations [19]. Research shows that climatic region influences the thermal sensation, which indicates comfort, such as a ‘slightly warm’ sensation in cold climates [20] or the expectation to feel ‘warm’ in warm climates [21]. Humphreys reported that in 57% of the 868 cases, the desired sensation was other than ‘neutral’. He revealed that ‘the data contain 868 comparisons of the actual and the desired sensation. On 57% of occasions the desired sensation was other than “neutral”’. He reported that ‘there were significant differences among the respondents in the thermal sensations they desired, confirming that some characteristically preferred to feel warmer than others’. He concludes that ‘if there is sufficient adaptive opportunity, people who feel ‘slightly warm’ perhaps desire at that time to feel ‘slightly warm’, while people who feel ‘slightly cool’ perhaps desire to feel ‘slightly cool’, and so on’. Han stated that ‘people in hot climates may prefer thermal state as ‘slightly cool’, while people in cold climates may use the words ‘slightly warm’ to denote their thermal preference’ [22]. Finally, Humphreys questioned the accuracy and application of the findings in the field of thermal comfort that are on the basis of the ‘neutral thermal sensation’ [11]. New scales were introduced to measure thermal comfort, such as ‘much too cool, too cool, comfortably cool, neutral, comfortably warm, too warm and much too warm’ [23]. Humphreys explains ‘the need to ascertain more precisely the desired thermal sensation on the scale led researchers to supplement it with a scale of thermal preference, which asked people whether they would prefer to feel warmer or cooler, or whether they desired no change’ [11]. The use of two scales, such as thermal sensation and preference, has been recommended [7,16]. Different scales of thermal preference have been introduced, including the ASHRAE nine-point thermal sensation scale, the EN-ISO 4-point thermal comfort scale, Bedford scale for thermal comfort [24], Fox scale for thermal preference [25], the six-point comfort scale [26], and the three-point comfort scale [27]. The combination of thermal sensation and comfort is confusing and separate scales are preferable [18]. Currently some field studies of thermal comfort use a combination of the ASHRAE seven-point thermal sensation scale and the three-point McIntyre scale [28], as presented in Table 2 [29]. However, the later does not clarify how much cooler or warmer occupants prefer. Therefore, their desired thermal sensation cannot be analysed [11].

Table 2: McIntyre scale for thermal preference [28]

I would like to be:		
Cooler	No change	Warmer
-1	0	+1

Humphreys and Hancock use the ASHRAE scale as a double enquiry method, as presented in Table 3 [11].

Table 3: The ASHRAE scale for double enquiry method used by Humphreys and Hancock [11].

How do you feel just now? Based on the [2]						
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
1	2	3	4	5	6	7
How would you like to feel just now? [30]						
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
-3	-2	-1	0	+1	+2	+3

The use of the ASHRAE seven-point scale of thermal preference combined with the seven-point thermal sensation scale has been recommended [18,19], as presented in

Table 1 and adopted in some studies [31,32]. Sherman points out the difference between thermal sensation and preference, as he explains that the PMV model 'is a measure of the thermal sensation (not preference)' [33]. 'Thermal neutrality is not necessarily ideal for a significant number of people and preferences for non-neutral thermal sensations are common, very asymmetrically around neutrality, and in several cases are influenced by season. Also, thermal sensations outside of the three central categories of the ASHRAE seven-point scale of thermal sensation do not necessarily reflect discomfort for a substantial number of persons' [34]. Mainly with the work of Humphreys, Nicol and de Dear, recently advanced research in thermal comfort is shifting away from simply considering the 'neutral thermal sensation', as other thermal sensations, which may be acceptable for the user, are considered important as well [35-40]. Despite all this effort, still the focus of thermal comfort literature and research is thermal neutrality, such as in [41-45].

3. Research Methods

This study questions the application of neutral thermal sensation in assessing thermal comfort. The thermal environment is considered as comfortable when the occupant reports a neutral feeling regarding the surrounding thermal environment. This study challenges this view, as other occupants may prefer other thermal sensations (e.g. slightly warm, warm, cool or slightly cool). Therefore, the application of thermal sensation and thermal preference of the occupants in four office buildings in Norway and the UK in the summer of 2012 were investigated. Field studies of thermal comfort were applied, survey questionnaires, environmental measurements (air temperature, relative humidity, mean radiant temperature) and follow up interviews were conducted. Quantitative regression is the main analysis method in the field studies of thermal comfort [10], which was applied in this study. The ASHRAE seven-point thermal sensation, thermal preference, comfort, and satisfaction (

Table 1) were the main questions on the survey questionnaire. The regression analysis was applied using a statistical analysis software (SPSS) on the PMV and survey variables, including comfort, satisfaction, thermal sensation, and preference. The probability of gaining results equal or beyond observation (P value) was examined [46]. Sedentary activities took place in the case study buildings. Overall, 313 responses were included in this study with a good range of age and gender and between 68 to 95 responses from each building, as demonstrated in Table 4.

Table 4: Case study information

Building and respondent information							
Buildings	**Floor area m^2**	**Workstation number per floor**	**Workstation size m^2**	**Considered workstations**	**M**	**F**	**City**
Building A	2000	100	10	95	53	42	Oslo
Building B	840	24	14	77	41	36	Oslo
Building C	1000	125	5	72	34	38	Inverness
Building D	1680	525	3.5	69	37	32	Aberdeen

4. Analysis and Results

In this research, good practice examples of the workplace that were expected to provide satisfactory thermal environment were studied in order to limit the impact of the building performance on occupants' views. In order to examine this, the thermal environments of the case study buildings were compared against the ASHRAE PMV model (2013) using the environmental measurements of the buildings. All buildings were expected to provide comfortable thermal conditions (i.e. 91% of the workstations were expected to be thermally comfortable). This suggested that the respondents' desire to change the thermal settings are more likely related to the individual requirements rather than the result of an uncomfortable thermal environment. Further statistical regression analysis was applied to investigate the relationship between the ASHRAE PMV model and variables including thermal sensation, thermal preference, comfort, and satisfaction. Thermal sensation is different from comfort and satisfaction in the ASHRAE seven-point scale. In thermal sensation, the response indicating comfort (i.e. neutral = 0) is placed in the middle of the scale. However, in comfort and satisfaction questions, very comfortable (+3) and very satisfied (+3) responses are at one end of the scale. Therefore, to compare these variables, thermal sensation is modified so that neutral is at one end of the scale, as follows:

- +3 = Neutral
- +2 = Slightly warm/slightly cool

- +1 = Warm/cool
- 0 = Hot/cold

Similar instructions are applied to thermal preference and the following four-point scale is used in the regression analysis:

- 4 = No change
- 3 = Slightly cooler/warmer
- 2 = Cooler/warmer
- 1 = Much cooler/warmer

The Predicted Mean Vote (PMV) analysis was applied to examine the thermal performance of the four buildings using the ASHRAE Thermal Comfort Tool [47]. The PMV was calculated using the thermal measurements (air temperature, relative humidity, mean radiant temperature) and observations (clothing and activity of users). The analysis indicated that the occupants of the four buildings are expected to feel neutral or slightly cool, as presented in Figure 1.

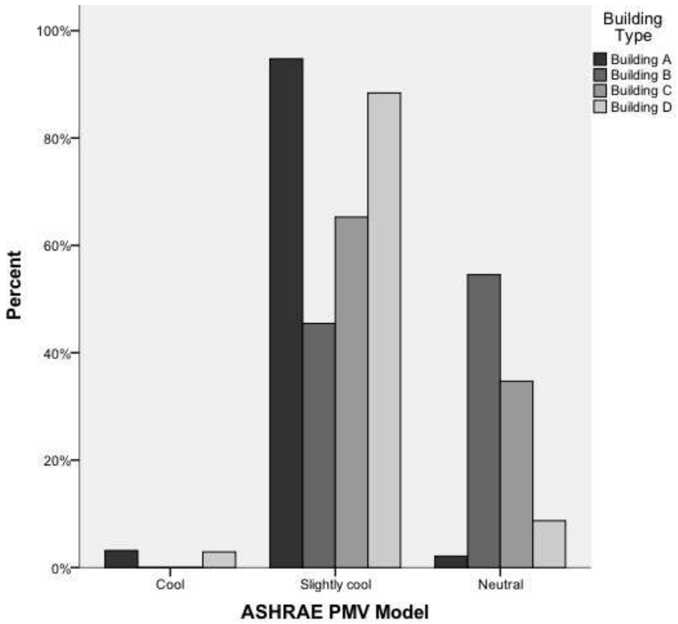
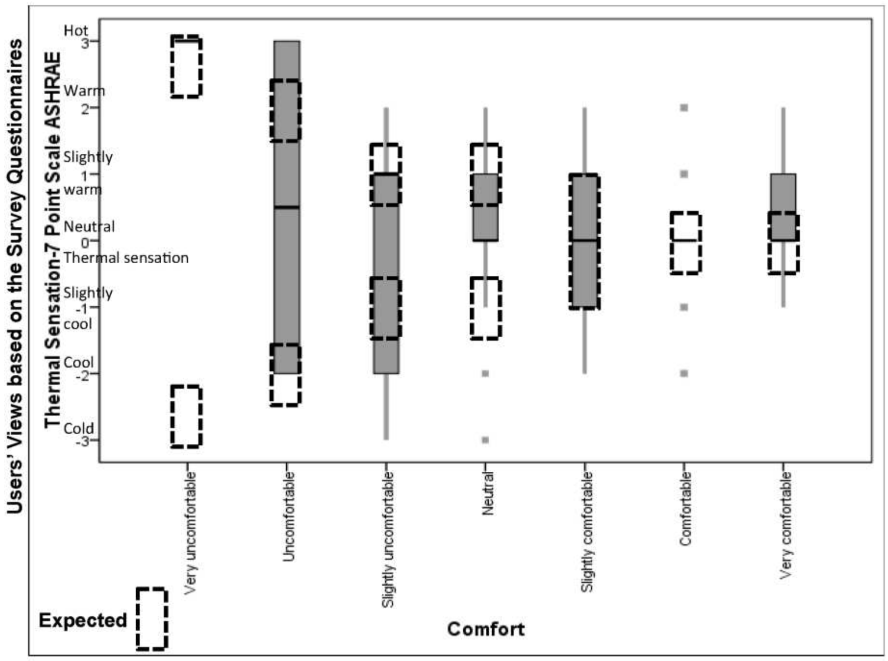


Figure 1: The PMV analysis

The regression analysis was applied on the PMV and survey variables, including comfort, satisfaction, thermal sensation, and preference. The analysis indicated no significant relationships between the PMV predictions and the variables: thermal sensation (P value = 0.084 > 0.05), thermal preference (P value = 0.185 > 0.05), comfort (P value = 0.569 > 0.05), and satisfaction (P value = 0.694 > 0.05). Although the PMV model predicted relatively good and similar thermal environments in all four buildings, this was not related to respondents' report of their thermal sensation, thermal preference, comfort, and satisfaction statuses. This indicated limited impact of the quality of the thermal environment on the comfort status of the respondents.

The SPSS linear regression analysis was applied on the relationship between thermal sensation and comfort. It showed that thermal sensation of respondents explained 13.2% of the variance in their comfort level. Every degree increase on the four-point thermal sensation scale towards 'neutral' improved comfort level of the user up to 0.565 on the ASHRAE seven-point scale towards 'very comfortable'. Overall, the analysis indicated a significant relationship between comfort and thermal sensation (P value = 0.000 < 0.05). Figure 2 is the boxplot of surveyed comfort and thermal sensation and the dashed rectangles show the expected response regarding the thermal sensation in accordance with the comfort level of the respondent. Participants, who felt comfortable, had a relatively small range of thermal sensation between 'neutral' and 'slightly warm'. In contrast, participants who felt uncomfortable had a much wider range of thermal sensations between 'cool' to 'hot'. Respondents, who felt the extremes of the thermal sensation, were more likely to be uncomfortable. It also showed comfort when respondents felt 'slightly warm', while discomfort when they felt 'neutral'.



Users' Views based on the Survey Questionnaires

Figure 2: Boxplot of comfort and thermal sensation, the ASHRAE seven-point scale

This study was looking for high quality environments that provided users with unconditional satisfaction and comfort. Therefore, from the ASHRAE seven-point scale, only two responses ('comfortable' and 'very comfortable') that represented a comfort status with confidence were considered as a 'comfortable' response. The same instruction was applied to evaluate satisfaction, as only 'satisfied' and 'very satisfied' responses were considered as 'satisfied'. Figure 3 shows the 'comfort' responses in accordance with thermal sensation status of the users. Comfortable respondents had a thermal sensation between 'slightly cool' to 'slightly warm', and most them felt 'neutral'. Participants with extreme thermal sensations were mainly uncomfortable. This is in line with the results of Figure 2. Figure 3 also shows that over 30% of the respondents with a neutral thermal sensation were not comfortable.

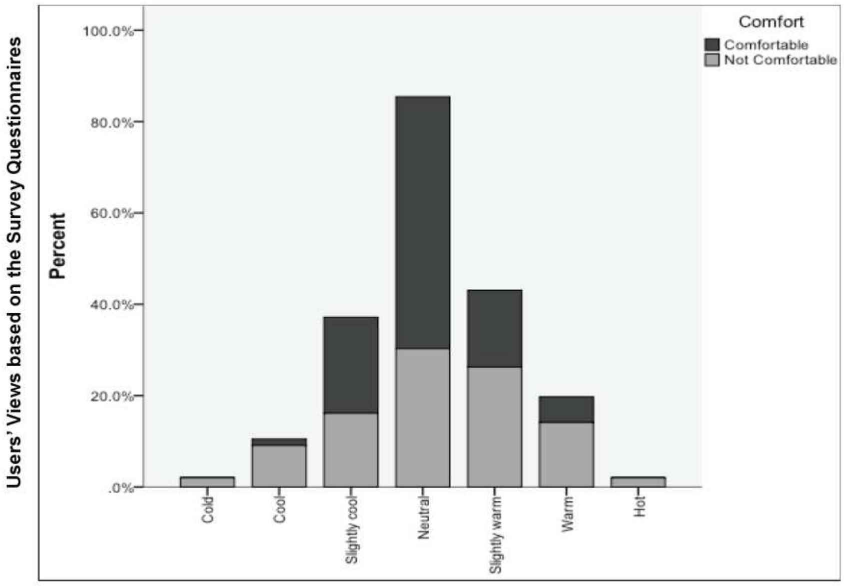


Figure 3: 'Comfortable' responses and thermal sensation

The SPSS linear regression analysis of thermal sensation and satisfaction indicated that 16.9% of the variance of satisfaction level can be explained by thermal sensation of the respondent. Every degree increase on the four-point thermal sensation scale towards 'neutral' improved satisfaction level of the user up to 0.734 on the ASHRAE seven-point scale towards 'very satisfied'. Overall, the statistics showed a strong relationship between the two variables (P value = 0.000 < 0.05). Figure 4 is the boxplot of satisfaction and thermal sensation and the dashed lines show the expected thermal sensation response in accordance with the satisfaction level of the respondent. 'Very satisfied' participants felt between 'slightly cool' to ‘slightly warm’, while ‘very dissatisfied’ users had a much wider range of thermal sensation from ‘slightly cool’ to ‘hot’. Respondents, who felt the extremes of thermal sensation, were more likely to be dissatisfied. However, some respondents with ‘warm’ or ‘cool’ thermal sensations report feeling ‘comfortable’, while some ‘dissatisfied’ participants report feeling ‘neutral’ regarding the thermal environment.

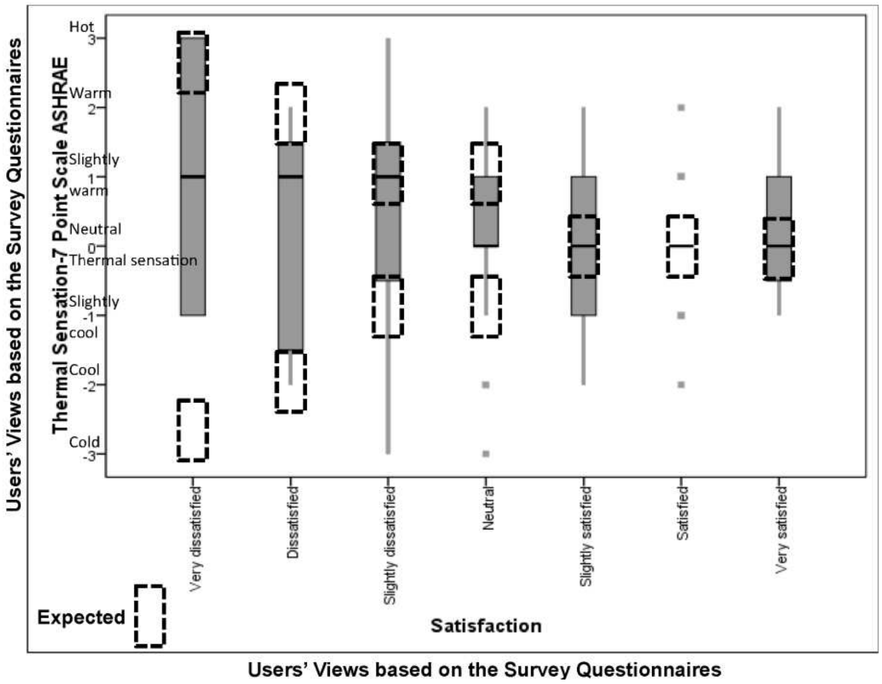


Figure 4: Boxplot of satisfaction and thermal sensation, the ASHRAE 7-point scale

As explained, only ‘satisfied’ and ‘very satisfied’ responses were considered as ‘satisfied.’ Figure 5 shows the relationship between ‘satisfied’ responses and thermal sensation of the users. Satisfied respondents had a thermal sensation between ‘slightly cool’ to ‘slightly warm,’ and most them felt ‘neutral’. Participants with extreme thermal sensations were mainly dissatisfied, which confirms the results of Figure 4. Figure 5 also reveals that over 30% of the occupants with a neutral thermal sensation were not satisfied.

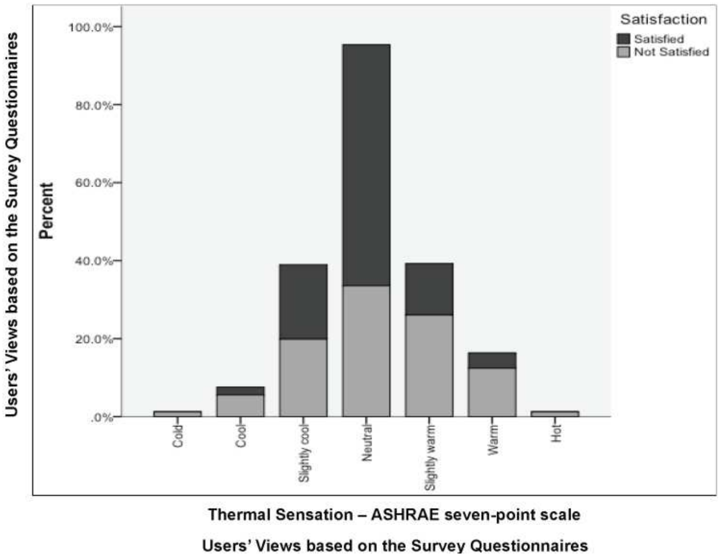


Figure 5: 'Satisfied' responses and thermal sensation

The SPSS linear regression analysis of thermal sensation and preference indicated that thermal preference explained 46.4% of the variance in thermal sensation, which was quite significant. There was a strong relationship between the two variables (i.e. P value = 0.000 < 0.05). Figure 6 is the boxplot of the two variables and the dashed lines show the expected thermal preference of the users based on their thermal sensation status. It shows that except for the cases of 'cold' and 'hot' thermal sensations, there is a consistency between thermal sensation and thermal preference of the user with a tendency to restore a 'neutral' sensation. For instance, respondents with a 'neutral' thermal sensation want 'no change' in the thermal environment and the majority of the respondents with a 'slightly warm' thermal sensation prefer a 'slightly cooler' thermal setting.

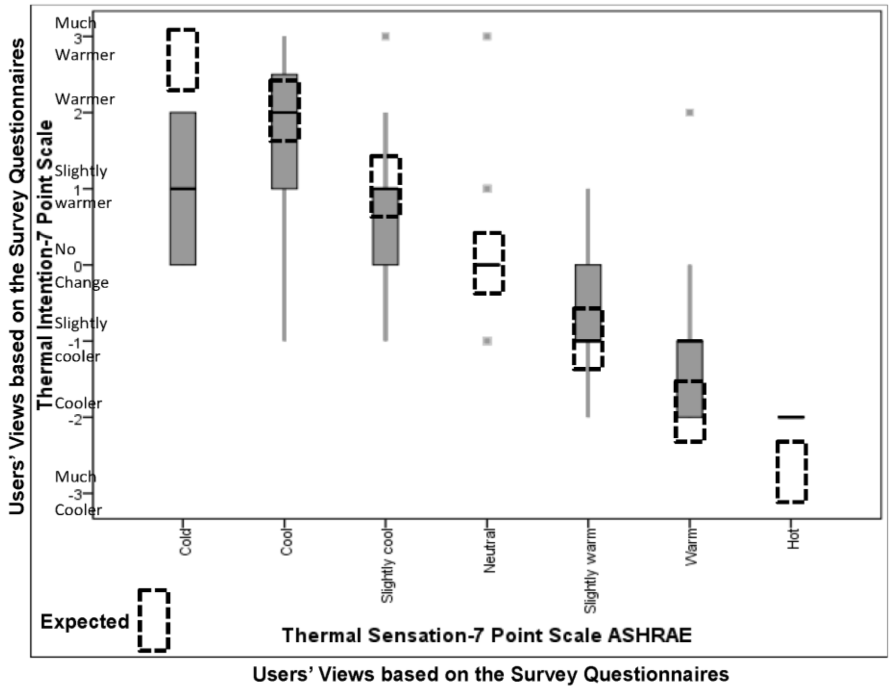


Figure 6: Boxplot of thermal preference and thermal sensation, the ASHRAE 7-point scale

Figure 7 shows thermal sensation of users in accordance with the status of their thermal preference. Majority of the respondents, who felt neutral, preferred no change in the temperature. The further their sensation was from neutral towards the extremes of hot and cold, the more desire they have to change the temperature. This confirms the results of Figure 6. Figure 7 also shows that over 20% of the respondents with a neutral thermal sensation wanted a change in temperature.

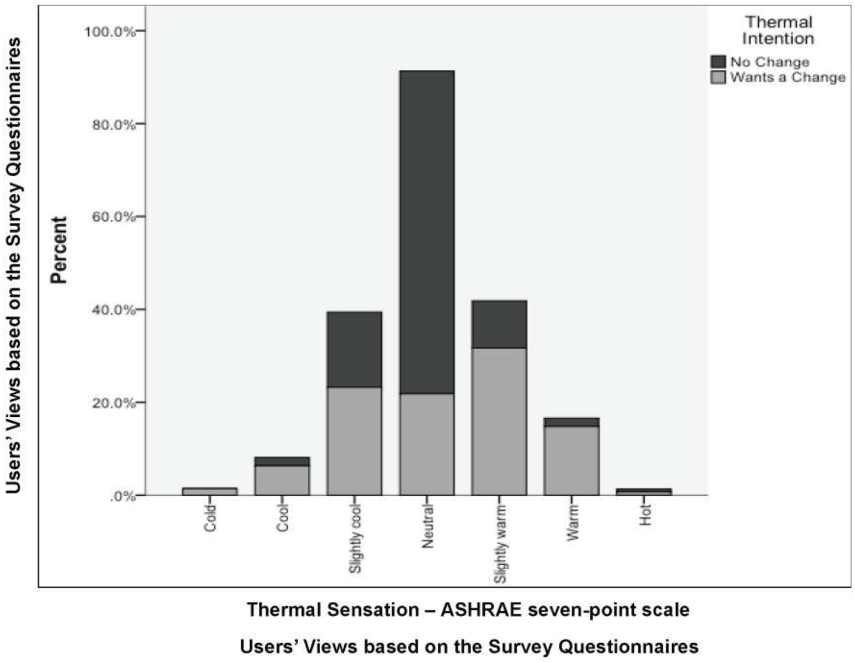


Figure 7: 'No change' thermal preference and thermal sensation

When thermal sensation and thermal preference were combined (thermal decision), 36% of the respondents did not want to feel neutral. 25 occupants (i.e. 8%) felt neutral but preferred to feel thermal sensations other than neutral. 77 respondents (i.e. 25%) already felt neutral but the thermal changes they wanted would not add up to a thermoneutral sensation. 13 respondents (i.e. 3%) wanted to feel beyond the range of slightly cool, neutral and cool, as they preferred to feel warm, hot, cool or cold. In the follow up interviews, 70% of the participants acknowledged individual differences in perceiving the thermal environment. When asked what thermal sensation they would prefer to feel when working, 40% of them wanted 'slightly cool' and 'cool' to feel fresh and not sleepy, and 30% preferred feeling 'slightly warm' to 'warm', due to the lack of movement and the sedentary nature of the work. Only 30% of them wanted a 'neutral thermal sensation' when working. Most members of this group considered thermoneutrality the 'obvious' choice.

5. Discussion and Conclusion

The results of this study suggest that neutral thermal sensation does not guarantee thermal comfort, as occupants may prefer to feel other sensations than neutral. The results indicated that 36% of the respondents did not want to feel neutral regarding the thermal environment. Although uncomfortable and dissatisfied occupants were more likely to feel other than neutral, to feel a neutral thermal sensation did not guarantee the feeling of comfort or satisfaction. Over 30% of the responses were not consistent between comfort, satisfaction and thermal sensation. This was in line with the findings of Humphreys and Hancook [11]. The follow up interviews revealed that 60% of the respondents did not want to feel neutral when working. These findings did not agree with some assumptions in the field of thermal comfort. For example, the findings did not agree with Hawkes' definition of thermal comfort as the 'intermediate point, when neither cold nor hot' [7]. This study questions the application of the 'neutral thermal sensation' as the basis of the standard 'comfort zone', as indicated in the ASHRAE Standard 55-2013. The findings of this study question the accuracy of the findings of other studies, in which thermoneutrality is the only measure of thermal comfort. This study suggests that the 'neutral thermal sensation' is not an accurate measure to assess thermal comfort. The results indicate that thermal preference is more accurate measure of thermal comfort. However, it does not reveal the current thermal state of the user. For example, knowing a respondent prefers a slightly warmer thermal environment at the time does not indicate whether they feel neutral, slightly cool or slightly warm at the time. Therefore, the combination of two measures, thermal sensation and thermal preference, is more likely to indicate human thermal comfort. This study recommends the application of the ASHRAE seven-point thermal sensation and preference (presented in

Table 1). It is recommended that individual differences in perceiving the thermal environment to be considered in the environmental design of the building. A degree of flexibility is suggested to allow the occupants to find their own comfort through adjusting the thermal environment to their requirements.

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