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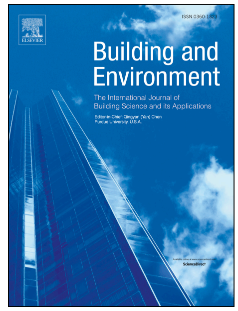

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Evaluation of Thermal Comfort in Building Transitional Spaces - Field Studies in Cardiff, UK

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Abstract

Transitional spaces have been widely applied in building designs. They may account for 10 to 40% of total volume in different types of buildings. Maintaining an acceptable level of thermal comfort for transitional spaces poses challenges to building designers and engineers. However, there is not in general a recommended acceptable comfort range for transitional spaces, nor are there specific thermal comfort prediction methods. This paper aims to investigate the thermal environmental performance and people's adaptive comfort in transitional spaces, by conducting field studies, which include on-site questionnaire surveys and physical measurements. Field studies were carried out for three selected case study buildings in Cardiff, each having some forms of transitional space. They were the National Assembly for Wales Senedd, the Hadyn Ellis Building and the Royal Welsh College of Music and Drama. The total responses from the questionnaire surveys were 736 and 580, for all buildings, during the summer period in 2017 and the winter period in 2018 respectively. This paper first presents the findings from the field studies, followed by in-depth analysis of human adaptability to thermal environment. Strong correlations were identified between clothing value and indoor operative temperature. People's adaptability to the thermal environment is confirmed, with nearly 80% of the respondents opting for self-adaptive actions to overcome uncomfortable situations. The identified 90% acceptability comfort band (-0.5<TSV<+0.5) were 4.0°C and 4.2°C for the summer period and the winter period respectively, implying that a fine control of the indoor temperature to maintain an acceptable comfort level is not necessary.

Keywords: Transitional spaces, thermal comfort, field studies, questionnaire survey, adaptability

1. Introduction

In many different kinds of buildings, transitional spaces are integrated with the architectural design. These spaces are claimed as "unavoidable spaces in non-domestic buildings", which may typically occupy between 10% - 40% of the total volume in different types of buildings [1]. Transitional spaces are defined as the spaces located in-between outdoor and indoor environments, which provide both a buffer space and physical link [2]. For transitional spaces, which serve as 'environmental bridges', connection between the interior and exterior environments and relaxation spaces are provided for the occupants to enjoy the surroundings. In these spaces, the occupants are able to experience the dynamic effects of the external climatic changes [3]. Different functions can be provided by transitional spaces, including seating area, circulation passage, entrance lobby, cafeteria and meeting places [4]. From an architectural aspect, transitional spaces can be physically connected to a building development or can be separated from it [5].

The development of the transitional space can be traced back to climate sensitive and social use of central courtyards in ancient design [6]. Transitional spaces have been used in building design for some 5000 years [7,8]. Courtyard design might be considered as the original idea of transitional spaces, which served as a climate modified and central social function space, providing natural ventilation for the internal spaces [9] A similar design was found in the 10th to 11th century BC in Chinese residential houses, named Siheyuan [10]. In the 18th century, other central courtyards were found in ancient Roman and Greek houses [11], where the term atrium originates from [12]. They formed the central room of the building, connecting to all the other chambers [13]. Atria were popular towards the end of the last century, especially in office buildings [14]. In recent decades, with advanced technologies and new materials, including glazing and structure, and computational modelling [15], transitional spaces have evolved into different types. Until the present decade, transitional spaces, especially in the form of atria, have become a dominant feature in built environments [6,15]. The evolution of transitional spaces is demonstrated through their prevalence as an architecture element in building designs. In addition, even though transitional spaces have gone through their evolution, the fundamental function still remains unchanged [16].

Although transitional spaces do not generally require a fine control of temperature or have comfort limits when compared to indoor spaces, maintaining an acceptable thermal comfort for such spaces is still a challenge to building designers [2]. Recent research has revealed that glazed façades lead to a strong interaction between external environment and indoor space, and thermal discomfort becomes a major issue. This may results in complaints from the building occupants [17–20].

Moreover, there is still a lack of research evidence relating to the thermal environment of transitional spaces [5,21,22]. The majority of previous research on the comfort environment of dynamic states, including transitional type spaces, such as corridors and atria, were conducted in climatic chambers, with only a few of them being validated through fieldwork studies [23]. Most of them only considered the human thermal response to stable environment conditions [24]. This may be the reason why transitional spaces are still not clearly addressed in the current comfort standards [25], and why there are no recommended acceptable indoor temperature ranges specified for thermal comfort in transitional spaces [26].

This paper therefore aims to investigate the thermal environmental performance and people's adaptability in transitional spaces by conducting field studies, which include on-site questionnaire surveys and physical measurements.

2. Research Methodology

The methodology adopted in this research included on-site questionnaire surveys and physical measurements in the transitional spaces of three existing buildings in Cardiff, namely, the National Assembly for Wales Senedd (NAfW), the Hadyn Ellis Building (HEB) and the Royal Welsh College of Music and Drama (RWCMD). They are shown in Figure 1. In order to optimise the proposed methodology for the main studies in these three buildings, a pilot study was performed in the transitional space of the Optometry Building of Cardiff University on 21st July 2017. The proposed methodology was then adjusted based on feedback from the pilot study, before carrying out the main studies. During the field studies, the indoor and outdoor environmental conditions were monitored at the same time as when the questionnaire surveys were carried out.

Figure 1. Surveyed buildings and their indoor environments

2.1 Surveyed Buildings

The selected buildings were all located in Cardiff. A single outdoor weather station was used in the study, where its distance from the selected buildings ranged from 0.1km to 2.8km. These buildings were selected based on the following major criteria:

1. the distance from the weather station shall be within 3km, in order to ensure the representation of the recorded weather data;
2. the buildings shall cover different functional types; and
3. the transitional spaces shall be large and publicly accessible, and where the response rate and thus representativeness of the questionnaire survey could be ensured.

The function of the surveyed buildings was quite different, but they were all open to the public during their opening hours. The windows of all the buildings were designed to be automatically opened under the control of Building Management System (BMS), which was aimed to enhance the ventilation during warm days so that a more desirable thermal comfort level could be maintained. In each of the selected buildings, field studies were carried out over a three-day period, in summer and winter. This included questionnaire surveys and physical measurements. Different ventilation modes were designed for each of these buildings, where the building can adopt natural ventilation or air conditioning mode to maintain the indoor comfort environment. Table 1 summarises the key characteristics of the surveyed buildings.

Table 1. Key characteristics of surveyed buildings

Surveyed building	NAfW	HEB	RWCMD
Building established	2006	2012	2011 (refurbished)
Building type	Public / Government	Academic	Academic / Cultural
Building area	5,120 m^2	9,740 m^2	4,400 m^2
No. of stories	3	5	3
Major façade type	Glazed	Glazed	Glazed
Windows open strategy	Automatic	Automatic	Automatic
Ventilation Mode	Mixed	Mixed	Mixed
Distance from weather station	2.8km	0.6km	0.1km
Survey dates (Summer Time)	19 August 2017 20 August 2017 26 August 2017	4 August 2017 8 September 2017 12 September 2017	20 September 2017 21 September 2017 22 September 2017
Survey dates (Winter Time)	6 January 2018 7 January 2018 13 January 2018	1 February 2018 2 February 2018 5 February 2018	20 January 2018 21 January 2018 22 January 2018
Survey period	10:30 – 16:30	08:30 – 17:30	08:30 – 19:00

2.2 Physical Measurements

Questionnaire surveys were carried out at the same time as the indoor environmental parameters were measured, which included air temperature, relative humidity, air velocity and black globe temperature. The accuracy of the instrumentations used for the field studies complied with the requirements stated in ASHRAE 55-2013 [27]. Table 2 summarises the details of the instruments that were used in the field studies.

Table 2. Measurement range and accuracy for the instruments used for the field studies

Parameter	Instrumentation model	Range	Accuracy	Accuracy requirements ASHRAE 55
Air temperature	Tinytag Ultra 2 Temperature and Relative Humidity Logger	-25°C - 85°C	±0.5°C (for range 0-40°C)	Minimum: ±0.5°C Ideal: ±0.2°C
Relative humidity	Tinytag Ultra 2 Temperature and Relative Humidity Logger	0% - 95%	±3% (at 25°C)	±5%
Black-globe temperature	Tinytag Talk 2 Temperature Logger (with 40mm black table-tennis ball)	-40°C - 125°C	±0.4°C (for range 0-70°C)	Minimum: ±2°C Ideal: ±0.2°C
Air speed	Lutron AM-4204 Anemometer	0m/s - 20m/s	±0.05m/s (for up to 1m/s)	±0.05m/s

Measurements were conducted at different locations across the indoor transitional spaces, including entrance lobby area, atrium area and café area. In order to ensure that the readings were representative throughout the surveyed area, and to identify the best measurement locations, a range of measurements was taken at different locations within each space. The average of the measured air temperatures at these locations were then calculated. The location where the measured air temperature was closest to the average air temperature was selected to place the measurement instruments. The air speed was measured at 15-minute intervals and all the other parameters were monitored at one-minute intervals. Each measurement location was set at 1.1m height from the floor. For the outdoor environmental parameters, data were recorded every five minutes by a weather station, which was installed on the rooftop of the Bute Building, the Architectural School of Cardiff University. The weather station data were recorded by a Campbell Instruments CR10 data logger. The air temperature and relative humidity were respectively measured by a Rotronic temperature and humidity probe with a radiation shield. Figure 2 illustrates the setups for the weather station and indoor measurement instruments.

Figure 2. Instrument setups for outdoor (left) and indoor (right) environments

2.3 Questionnaire Surveys

A standardised questionnaire was developed to collect subjective data from the building occupants for comfort evaluation in the specified locations of the surveyed buildings. As shown in Appendix I, 24 questions were included in the questionnaire, which adopted a combination of open-ended, partially closed-ended and predominantly closed-ended questioning approaches. 7-point scale and 5-point scale methods were used for the thermal sensation questions and thermal and sunlight preference questions respectively, as presented in Table 3. In order to understand people's adaptability to their thermal environment, an open question "how would you overcome uncomfortable situations, if any" was included in the questionnaire. Additional data collected from the questionnaire included the demographic data, purpose of using the spaces, activity level, clothing insulation, time spent at the interviewed location, previous space locations and time spent in previous space, and feedbacks and previous thermal experience in the interviewed location. Some subjective data such as clothing insulation and activity level were collected by giving a list of pre-set options with an open option which allowed respondents to fill in the answer that was out of the options. The options chosen by the respondents were then converted into quantitative figures according to ASHRAE Standard 55-2013 [27] and ISO 7703:2005 [28]. Building users were randomly selected within the transitional spaces of the surveyed buildings to carry out the questionnaire survey. In order to ensure the respondents had sufficient time to experience the thermal environment within the surveyed buildings, people who just entered the buildings from outdoor spaces would not be chosen for interviews. They were interviewed at least 5 minutes after they entered the buildings. The average period of stay in the transitional spaces for the respondents in NAfW, HEB and RWCMD were 26.5, 65.1 and 37.6 minutes respectively. Each survey was carried out by a means of a structured interview which took approximately 10 minutes to complete.

Table 3. Sensation and preference scale used in the survey

Scale	Overall Thermal Feeling	Thermal Comfort Sensation	Humidity Sensation	Air Movement Sensation	Thermal Preference	Sunlight Preference
+3	Very pleasant	Hot	Very humid	Very draughty	-	-
+2	Moderately pleasant	Warm	Moderately humid	Moderately draughty	Much warmer	Much more
+1	Slightly pleasant	Slightly warm	Slightly humid	Slightly draughty	A bit warmer	A bit more
0	Neutral	Neutral	Neutral	Neutral	No change	No change
-1	Slightly unpleasant	Slightly cool	Slightly dry	Slightly still	A bit cooler	A bit lesser
-2	Moderately unpleasant	Cool	Moderately dry	Moderately still	Much cooler	Much lesser
-3	Very unpleasant	Cold	Very dry	Very Still	-	-

2.4. Data Analysis

The data collected from the field studies were first compiled into spreadsheets and then analysed using the Statistical Package for Social Sciences (SPSS) version 23. Data were separately analysed according to surveyed buildings and specified locations within the buildings. In order to assess the correlation between pairs of variables, Pearson correlation coefficients were computed. The outcomes were analysed based on two significance levels, which were interpreted as average statistical significance ($p<0.05$) and high statistical significance ($p<0.01$).

3. Results and Analysis

3.1 Descriptive Analysis

The total number of responses collected from the questionnaire surveys were 736 and 580 during the summer period and the winter period respectively. Throughout the summer period, 282, 207 and 247 surveys were collected from the NAfW, HEB and RWCMD respectively; throughout the winter period, 198, 155 and 227 surveys were collected from the NAfW, HEB and RWCMD respectively. As the building functions and settings in the indoor transitional spaces of these buildings were different, the monitored and surveyed figures were different in different buildings. Details are summarised in Table 4.

The NAfW is a government building that is open to the public. During the summer period, because a special event “Poppies – weeping window” was held during the field study, a significant number of respondents were visitors to the building. Since no special event was held during the survey in the winter period, the number of collected surveys was reduced. Guided tours took place regularly in the atrium space on the Ground Floor at designated times. The major purpose for visitors in the atrium was for the tours which led to lesser collected responses from the atrium part of the space. By contrast, the majority of responses were collected from the exhibition area and café area on the First Floor. The average activity level of the respondents was higher than the other two surveyed buildings, owing to a larger portion of people who walked or stood to watch the exhibition or to appreciate the building’s architectural design or functional use. The measured indoor air temperature was lowest when compared to the other two surveyed buildings. For the summer period, the building was naturally ventilated. The windows were opened to keep the building ventilated at the time of the questionnaire survey. For the winter period, all the windows were closed and a trench heating system in the perimeter zones of the building was operated to maintain the indoor air temperature. However, even though the heating system was operating, the measured indoor temperature during the winter-time was lower than the other two surveyed buildings by at least 5.6°C. The major reasons were that the outdoor air temperature was lowest during the investigation period, in comparison with the other buildings, and that the space heat delivery were far away from the occupied areas and the measurement points.

The HEB is an institutional research building that provides facilities such as offices, laboratories, meeting spaces, seminar, and lecture rooms for university students or researchers involved in various types of academic activities. As most of the respondents were undergraduate and postgraduate students, the average age of the respondents was lower than that of the NAfW. Since a higher portion of respondents used the transitional spaces for resting and dining, and there were more chairs and sofas set up for the building users, most respondents were seated. Therefore, the average activity level was lower than the NAfW. During the survey period in the summer-time, the windows were closed most of the time. On some occasions, when the temperature rose up, the windows were opened to adopt natural ventilation. In the winter-time, all the openings were closed during the survey period. During the survey period, an underfloor heating system was operated, with a floor surface temperatures ranged between 28°C to 30°C.

For the RWCMD, as the academic term had started when the questionnaire survey was carried out, even more respondents were undergraduate and postgraduate students, when compared to the HEB. Therefore, the average age of respondents from the RWCMD was the lowest among all the surveyed buildings. There were even a greater number of chairs and sofas provided for the building users in the atrium space and café area when compared to HEB. In addition, people in the transitional spaces tend to stay there for academic discussion, resting and dining. Therefore, the average activity level of the respondents was lowest among all the surveyed buildings where the respondents were mainly seated during the survey periods. Most of the respondents used the transitional spaces for waiting, resting and meetings. During the survey period in both the summer-time and winter-time, the windows were closed all the time. This may explain why the average monitored indoor temperature was higher than the other buildings during the summer time. A trench heating system and fan coil unit system were operated to provide heating to the atrium space and café area respectively during the winter-time. Therefore, even though the outdoor temperature was about 6°C during the survey period, the average indoor temperature could still be maintained at 21.6°C.

Table 4. Summary of the surveyed and monitored results

		NAfW		HEB		RWCMD	
		Summer	Winter	Summer	Winter	Summer	Winter
Total responses (N)		282	198	207	155	247	227
Male respondents		110 (39%)	90 (45%)	81 (39%)	56 (36%)	115 (47%)	83 (37%)
Female respondents		172 (61%)	108 (55%)	126 (61%)	99 (64%)	132 (53%)	144 (63%)
Age	Mean	42	43	32	29	26	26
	SD	18	18	10	11	10	13
Clothing value (clo)	Mean	0.50	1.18	0.60	0.92	0.60	0.84
	SD	0.17	0.33	0.20	0.32	0.20	0.30
Activity level (met)	Mean	1.44	1.67	1.30	1.31	1.18	1.27
	SD	0.48	0.47	0.47	0.48	0.46	0.53
Outdoor temperature (°C)	Mean	18.1	5.4	16.6	6.3	16.4	5.9
	SD	2.3	1.4	1.8	1.6	1.3	2.0
Indoor temperature (°C)	Mean	20.9	16.0	22.8	22.6	22.9	21.6
	SD	1.3	0.8	1.0	1.3	0.9	1.3
Relative humidity (%)	Mean	43.6	44.7	45.3	30.5	57.3	41.4
	SD	5.3	4.2	9.3	3.2	6.8	2.4

*** Temperatures shown were the record taken during the time when the questionnaire survey was conducted**

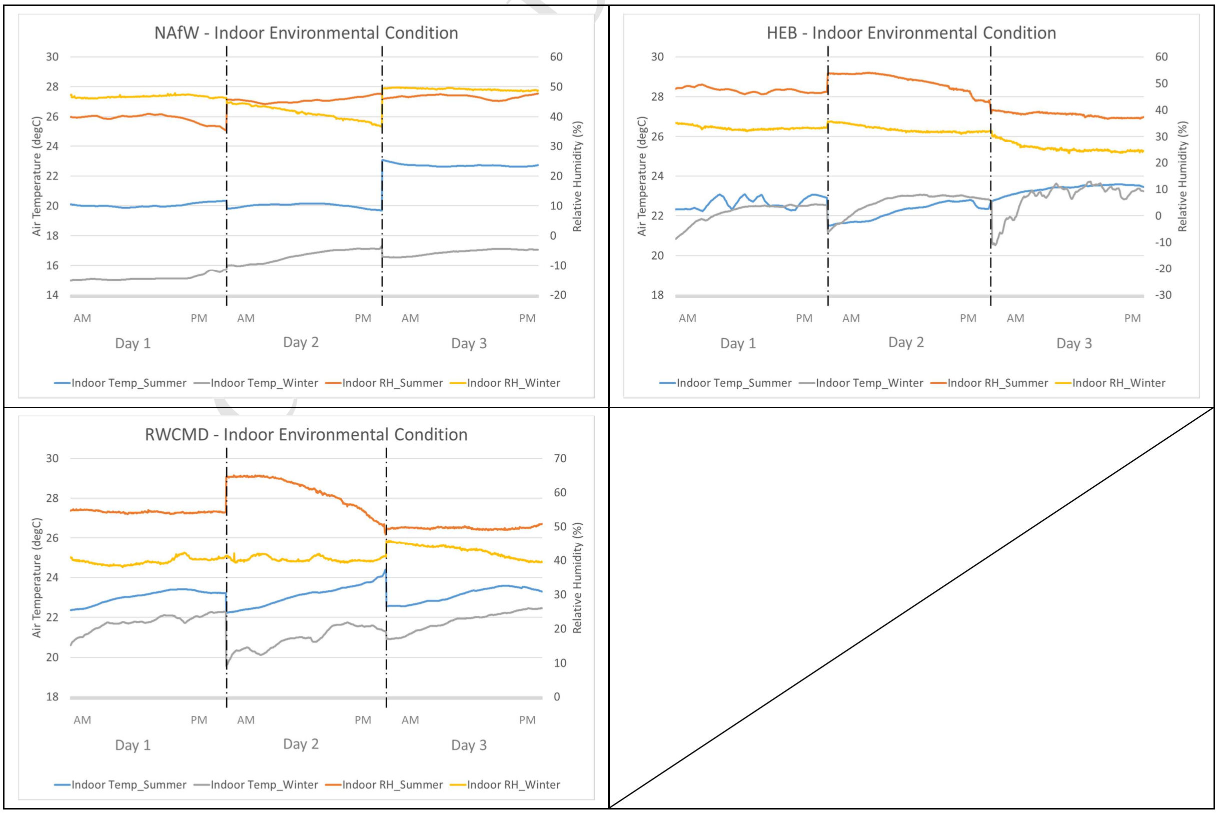

Figure 3. Physical measurement results for NAfW, HEB and RWCMD

Figure 3 illustrates the physical measurement results of the average indoor air temperature and relative humidity which were monitored during the field studies in both summer and winter time. Figure 4 illustrates the frequency distribution chart of the thermal sensation votes (TSV) that were collected from the questionnaire surveys from the three surveyed buildings. The thermal sensation distribution was similar among these buildings for both the summer and winter periods, where the majority of respondents voted for “neutral” and the others tended to have a warmer feeling (i.e. TSV>0).

For the summer period, some 85%, 83% and 76% of the respondents were found in the 80% acceptability comfort band (-1≤TSV≤+1), as defined by ISO 7730:2005 [28], for the NAfW, HEB and RWCMD respectively. In addition, for the question about the overall thermal feeling of the building, some 94%, 82% and 91% of the respondents felt pleasant (i.e. voted for +1 or higher), for the NAfW, HEB and RWCMD respectively. The average vote for the overall thermal feeling for the NAfW (mean: 2.25; SD: 0.96) was higher than that for the HEB (mean: 1.58; SD: 1.27) and the RWCMD (mean: 1.89; SD: 1.08). In summary, for all three surveyed buildings, people felt thermally comfortable in the transitional spaces during the summer period.

For the winter period, a slightly smaller number of respondents fell within the 80% acceptability comfort band when compared to the summer period, being some 82%, 81% and 78% for the NAfW, HEB and RWCMD respectively. Similarly, the number of respondents who felt pleasant about the overall thermal feeling of the buildings was also reduced, except for the HEB. Some 88%, 91% and 82% of the respondents voted for pleasant for the NAfW, HEB and RWCMD respectively. The average vote for the overall thermal feeling for the HEB (mean: 1.94; SD: 0.98) was higher than the other two surveyed buildings, that is, the NAfW (mean: 1.92; SD: 1.10) and the RWCMD (mean: 1.72; SD: 1.28). Even though the number of respondents who voted for an overall thermal feeling as pleasant was reduced, the portion was still over 80%. In summary, for the winter period all the three surveyed buildings were able to provide thermally comfortable transitional spaces for their occupants.

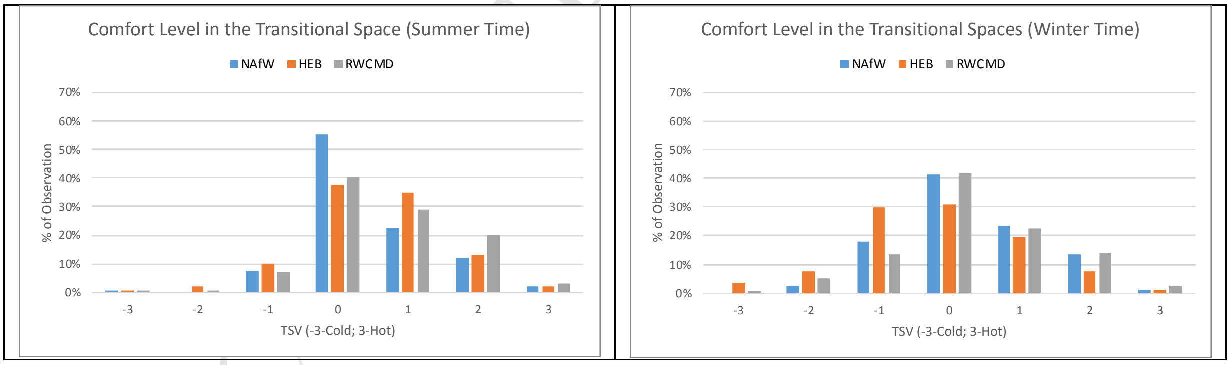

Figure 4. Frequency distribution of thermal sensation votes (TSV) in different transitional spaces during the summer period (left) and the winter period (right)

3.2 Correlation Analysis

In order to evaluate the correlation between different parameters and to filter out the appropriate parameters, a detailed analysis was carried out, using a Pearson (2-tailed) correlation analysis within the SPSS software. By inputting 39 parameters, including the questionnaire surveyed data, the measured environmental parameters, and the calculated comfort indexes of indoor operative temperature and PMV and PPD indexes, results were generated with a 1,482 Pearson correlation. Only the pairs of parameters that had a significant statistical correlation were then chosen for detailed analysis. These included the clothing value vs indoor operative temperature and outdoor temperature, and TSV vs indoor operative temperature and outdoor temperature. Table 5 and Table 6 below summarise the correlation results between clothing values and the temperature data, and between TSV and the temperature data respectively. The correlation was considered to have an average statistical significance when $p<0.05$; and a strong statistical significance when $p<0.01$.

It was found that clothing value correlated better with indoor operative temperature than with outdoor temperature. The relationship was stronger for the NAfW and the RWCMD during the summer period and the winter period respectively.

Table 5. Correlation results for clothing values of all surveyed buildings

	Clothing Value (Clo)					
	NAfW		HEB		RWCMD	
	Summer	Winter	Summer	Winter	Summer	Winter
Indoor Operative Temperature (℃)	-0.384**	-0.145*	-0.260*	-0.185*	-0.145*	-0.312**
Outdoor Temperature (℃)	-0.386**	-0.144*	-0.072	-0.125	-0.107	-0.146*

***significant at p<0.05**
****significant at p<0.01**

In order to evaluate people's thermal adaptability, TSV against indoor operative temperature, indoor dry-bulb temperature and outdoor temperature, were filtered out respectively for further investigations. It was found that TSV had the strongest correlation with indoor operative temperature among the other comparisons, during both the summer and winter periods. Therefore, indoor operative temperature was selected for a detailed regression study.

Table 6 Correlation results for thermal sensation vote (TSV) of all surveyed buildings

	Thermal Sensation Vote (TSV)					
	NAfW		HEB		RWCMD	
	Summer	Winter	Summer	Winter	Summer	Winter
Indoor Operative Temperature (℃)	0.162**	0.160*	0.165*	0.135**	0.135*	0.308**
Indoor Dry-bulb Temperature (℃)	0.153*	0.158*	0.131	0.128*	0.139*	0.245**
Outdoor Temperature (℃)	0.156**	0.088	0.133	0.036	0.032	0.002

***significant at p<0.05**
****significant at p<0.01**

3.3 Investigation of Influence of Indoor Operative Temperature and Outdoor Temperature on Clothing Value

The reported respondents' clothing in the questionnaire surveys were converted into numerical values, with reference to ASHRAE Standard 55-2013 [27] and ISO 7703:2005 [28]. In order to reduce the impact of outliers in the database, a binning method, which is common in comfort research [29–32], was adopted by taking the weighted averages for every half-degree-Celsius bin. Figure 5 illustrates the linear regression plots between the average clothing value and the indoor operative temperature and outdoor temperature respectively for the summer period.

For the correlation of clothing value against indoor operative temperature, the linear relationship was found to be strong, with a coefficient of determination (r2) ranging from around 0.71 to 0.91. Negative gradients were identified for all the cases. In other words, the higher the indoor operative temperature, the lower was the clothing value.

Similar correlations were conducted between clothing value and outdoor temperature. Similar relationships between outdoor temperature and clothing value were identified, only the correlation was weaker than the comparison with indoor operative temperature. The coefficient of determination (r2) ranged from 0.23 to 0.41. The identified gradients were the same, which were negative, as the correlations against indoor operative temperature.

Figure 5. Influence of indoor operative temperature and outdoor temperature on clothing value (summer period)

The linear regression plots between the average clothing value and the indoor operative temperature and outdoor temperature respectively for the winter period are shown in Figure 6. The plot between the clothing value and indoor operative temperature exhibited a strong correlation, with the coefficient of determination (r2) ranging from 0.76 to 0.83. The gradients identified for all the cases were negative. In other words, the higher the indoor operative temperature, the lower was the clothing value.

The relationships between outdoor temperature and clothing value were found similar However, the correlation was weaker than the comparison against indoor operative temperature. The coefficient of determination (r2) was ranged from 0.16 to 0.22. Similarly, the gradients of the linear relationship were negative.

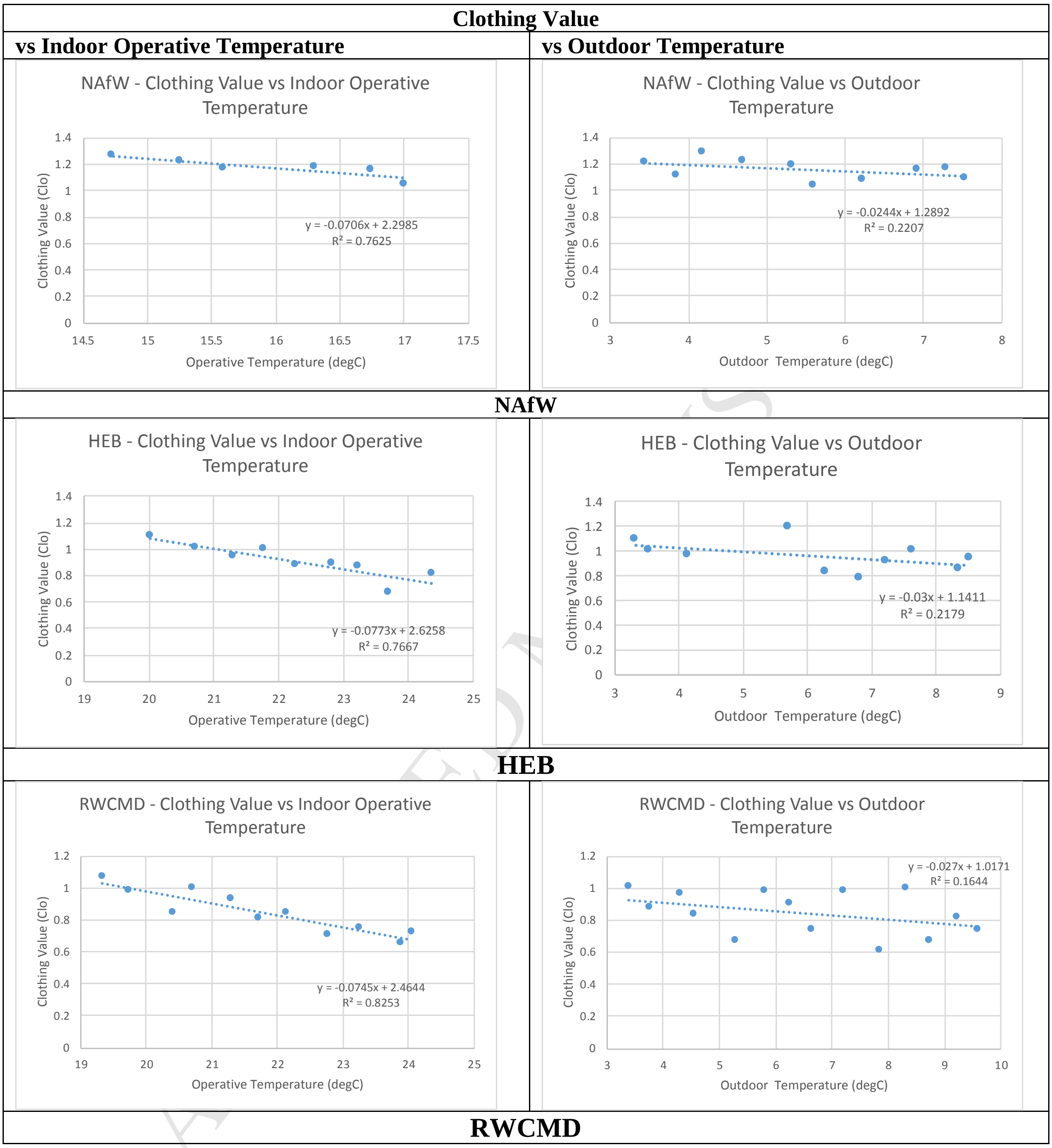

Figure 6. Influence of indoor operative temperature and outdoor temperature on clothing value (winter period)

3.4 Investigation of Actions that People Would Take to Overcome Uncomfortable Situations

An open question was asked in the questionnaire about how the respondents would act to overcome uncomfortable situations. For the summer period, out of the 736 surveyed questionnaires in total for the three surveyed buildings, the response rate for this question was 320, or 43.5%. For the winter period, the response rate for the question was 259, or 44.7% for the 580 collected surveyed questionnaires. As some of the people gave more than one answer, the number of collected answers from the respondents were 339 and 298, for the summer period and winter period respectively. As it was an open question, the use of words was different from different answers but they can basically be grouped into nine categories, which are "adjust clothing", "use mechanical means", "drink/eat", "move/leave from the uncomfortable location", "report to building staff", "do exercise", "close the openings", "improve the architectural design" and "other". For example, answers such as "take off jackets", "add a layer of clothing" and "put scarf / cardigan on" were classified as "adjust clothing"; answers such as "have a cup of coffee", "eat a burger" and "drink water" were grouped into "drink/ eat"; and rare answers such as "talk my way through" and "more light" were classified as "other". Table 7 summarises the details about the actions that respondents would take to overcome uncomfortable situations.

Table 7. Summary of respondents' actions to overcome uncomfortable situations

Categorised actions to overcome uncomfortable situations	**NAfW**		**HEB**		**RWCMD**		**Total**	
	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
Adjust clothing	55 (54%)	50 (46%)	43 (44%)	37 (59%)	71 (50%)	71 (56%)	**169 (50%)**	**158 (53%)**
Move / Leave from the uncomfortable location	23 (23%)	14 (13%)	14 (14%)	12 (19%)	35 (25%)	22 (17%)	**72 (21%)**	**48 (16%)**
Use mechanical means	11 (11%)	19 (17%)	12 (12%)	5 (8%)	11 (8%)	12 (10%)	**34 (10%)**	**36 (12%)**
Close the openings	1 (1%)	0 (0%)	16 (16%)	0 (0%)	6 (4%)	7 (6%)	**23 (7%)**	**7 (2%)**
Drink / Eat	4 (4%)	13 (12%)	4 (4%)	4 (6%)	10 (7%)	2 (2%)	**18 (5%)**	**19 (6%)**
Other	2 (2%)	2 (2%)	4 (4%)	2 (3%)	6 (4%)	4 (3%)	**12 (4%)**	**8 (3%)**
Report to building staff	2 (2%)	1 (1%)	3 (3%)	3 (5%)	1 (0%)	2 (2%)	**6 (2%)**	**6 (2%)**
Do exercise	3 (3%)	6 (6%)	2 (2%)	0 (0%)	0 (0%)	2 (2%)	**5 (2%)**	**8 (3%)**
Improve the architectural design	0 (0%)	4 (4%)	0 (0%)	0 (0%)	0 (0%)	4 (3%)	**8 (3%)**	**8 (3%)**
Total response rate	**101 (30%)**	**109 (37%)**	**98 (29%)**	**63 (21%)**	**140 (41%)**	**126 (42%)**	**339**	**298**

Out of these categories, “adjust clothing”, “drink / eat”, “move / leave from uncomfortable location” and “do exercise” can be treated as self-adaptive actions. Nearly 80% of the respondents opted for self-adaptive actions to overcome uncomfortable situation. In other words, a vast majority of people tended to adapt themselves to the thermal environment in order to make themselves feel more thermally comfortable, rather than attempting to change the building operations such as openings and air conditioning systems. Among these self-adaptive measures, “adjust clothing” was the most selected action by the respondents for all the three surveyed buildings. It constituted about half of the categorised actions. Similar distribution of the categorised actions that respondents would take to overcome the uncomfortable situations was also observed from the questionnaire surveys.

3.5 Investigation of Neutral Temperatures

Neutral temperature is defined as the temperature at which people reach their thermal neutrality, and they feel neither cool nor warm [33]. When neutral temperature can be achieved, most of the people would feel thermally comfortable and accept the thermal environmental condition [27]. In order to identify the neutral temperature for the three selected case buildings, weighted linear regressions were performed. A binned method was adopted by setting the increments of indoor operative temperature at half-degree-Celsius in order to eliminate the outliers [29–32]. The mean TSV of each bin was determined. Linear regression, which has been used to investigate thermal comfort datasets since 1930s [34,35], was adopted to evaluate the neutral temperatures in this research. Figure 7 shows the regression results of the mean TSV against indoor operative temperature with standard deviation shown for each bin. The neutral temperatures were then identified by solving the regression equipment for TSV = 0.

For the summer period, a strong linear relationship between the mean TSV and the indoor operative temperature was identified, where the coefficient of determination (r2) ranged from 0.62 to 0.70. As the gradients were all positive, it implied that the higher the indoor operative temperature, the higher was the TSV. In other words, the building occupants felt warmer when the indoor operative temperature rose. The summer period neutral temperatures evaluated for the NAfW, HEB and RWCMD were 19.3°C, 21.2°C and 21.0°C respectively.

The linear relationship between the mean TSV and the indoor operative temperature that was identified for the winter period was wider, where the coefficient of determination (r2) ranged from 0.65 to 0.86. Similar to the case in the summer period, the gradients were all positive, implying that the higher the indoor operative temperature, the higher was the TSV. For the HEB and RWCMD, the correlations and the resulted neutral temperatures were similar when compared to the summer period. However, as the measured indoor operative temperature in the NAfW was lower during the field study, the resulted neutral temperature was found lower than that for the summer period. In summary, the neutral temperatures evaluated for the NAfW, HEB and RWCMD were 16.9°C, 20.9°C and 20.7°C respectively.

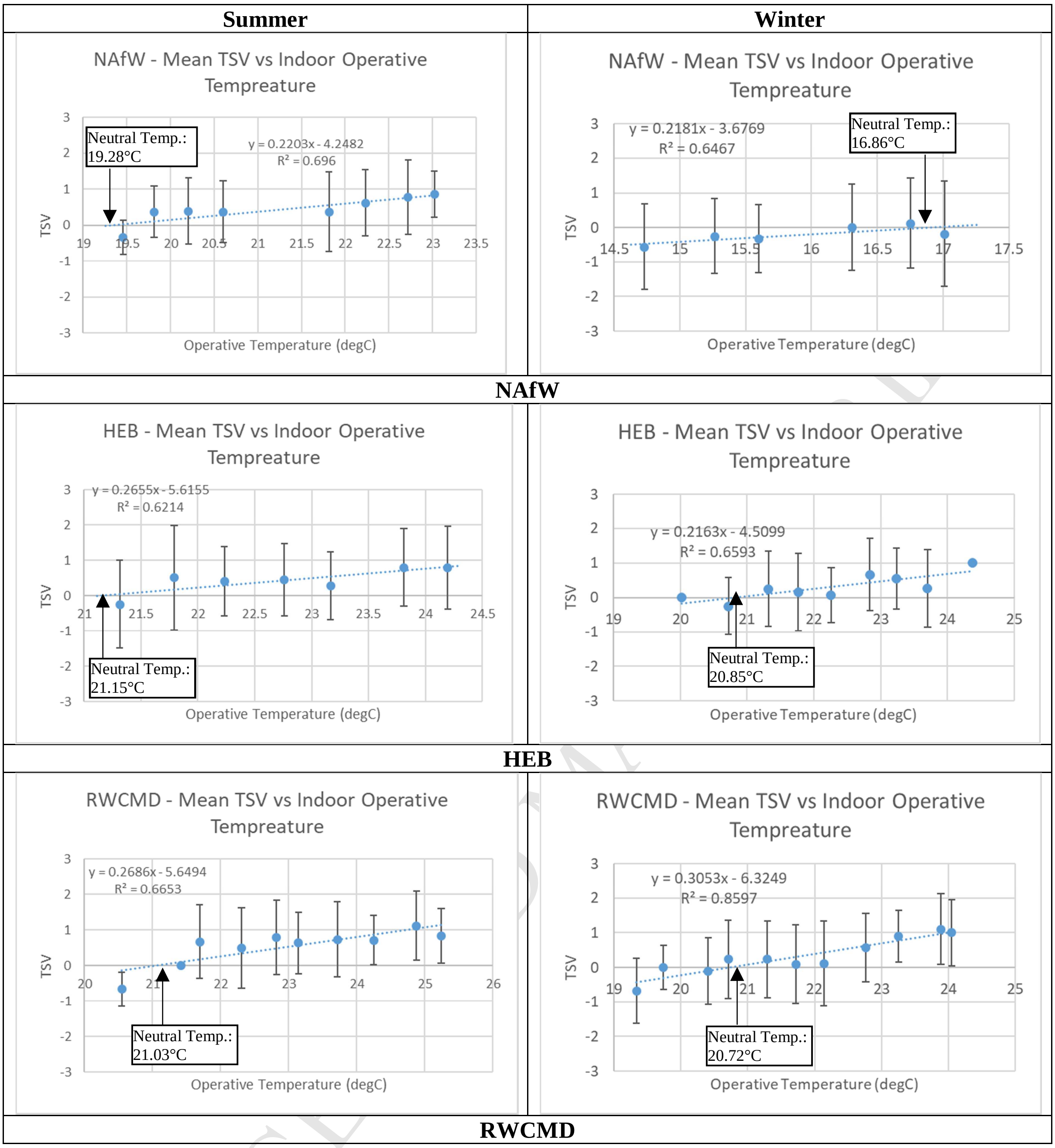

Figure 7. Relationship between thermal sensation vote (TSV) and indoor operative temperature

3.6 Investigation of Preferred Temperatures

Preferred temperature represents the point at which people do not prefer either cooler or warmer. It is a subjective feeling about people's pleasantness or unpleasantness about their thermal environment, which may change with seasonality and climate. This can be explained by a concept called 'alliesthesia' [36]. The neutral temperature might not be the same as preferred temperature [37]. People tend to have higher preferred temperature than neutral temperature in cold climate; and lower preferred temperature than neutral temperature in hot climate [38].

Weighted linear regression models and binned methods at half-degree-Celsius were adopted to identify the preferred temperatures for the surveyed buildings [19,39,40]. A 5-point scale method was used to identify the respondents' thermal preference votes (TPV) on the thermal environment of the surveyed locations. The responses collected were classified into two groups. They were "prefer cooler" and "prefer warmer", which were defined as TPV<0 and TPV>0 respectively. After binning the TPV at each half-degree-Celsius increment, the sample size of TPV (in % of observation) for different groups was regressed against the indoor operative temperature separately. Figure 8 shows the results for the preferred temperatures for the surveyed buildings. The preferred temperatures determined for the NAfW, HEB and RWCMD were 21.2°C, 21.6°C and 22.7°C respectively for the summer period. For the winter period, there was not any intersection between the "prefer cooler" and "prefer warmer" trends for NAfW as the indoor operative temperature was low. Therefore, the trend lines were extrapolated to identify the preferred temperature. In summary, the preferred temperatures for the NAfW, HEB and RWCMD were 21.5°C, 22.9°C and 22.5°C respectively.

Figure 8. Preferred indoor operative temperatures of the building occupants

3.7 Investigation of Acceptable Temperature Ranges

The regression models developed in Figure 7 were used to identify the building occupants' thermal acceptability at the surveyed locations. The 80% and 90% acceptability comfort bands represent respectively that 80% and 90% of occupants declare a thermal environment as comfortable and they are defined as -1<TSV<+1 and -0.5<TSV<+0.5 respectively [28]. Table 8 summarises the evaluated results for the acceptable temperature ranges and the preferred and neutral temperature that were identified in previous sections.

For the summer period, the average preferred temperature and the average neutral temperature of the three surveyed buildings were 21.8°C and 20.5°C respectively. The NAfW had the lowest preferred and neutral temperature while the RWCMD had the highest preferred and neutral temperature. The average range for the 80% acceptable temperature range of the surveyed buildings was 8.0°C wide, which was brought down to 4.0°C wide for the 90% acceptable temperature range.

For the winter period, the preferred temperature for the NAfW cannot be identified as the linear trends for the thermal preferences (prefer cooler and prefer warmer) did not cross with each other. For the other buildings, the preferred temperatures were higher than that for the summer period, which were 22.9°C and 22.5°C for the HEB and the RWCMD respectively. In terms of natural temperature, except for the NAfW where the neutral temperature was lower than that for the summer period, the neutral temperatures identified for the HEB and the RWCMD were similar to that for the summer period. The average range for the 80% acceptable temperature range of the surveyed buildings was 8.3°C wide, while it was down to 4.2°C wide for the 90% acceptable temperature range.

Table 8. Summary of preferred temperature, neutral temperature and acceptable temperature ranges

	NAfW		**HEB**		**RWCMD**	
	Summer	Winter	Summer	Winter	Summer	Winter
Preferred Temperature (°C)	21.2	21.5	21.6	22.9	22.7	22.5
Neutral Temperature (°C)	19.3	16.9	21.2	20.9	21.0	20.7
80% Acceptable Temperature Range (°C)	14.7–23.8	12.3–21.4	17.4–24.9	16.2–25.5	17.3–24.8	17.4–24.0
90% Acceptable Temperature Range (°C)	17.0–21.6	14.6–19.2	19.3-23.0	18.5–23.2	19.2–22.9	19.1–22.4

4. Discussions

The data analysis showed that the thermal comfort level was generally acceptable by the building users A large portion of the respondents (>82% for both the summer and the winter periods) voted the overall thermal feeling as "pleasant" (>+1 vote) in all the three surveyed buildings. Moreover, more than 80% of the respondents voted the TSV within the 80% comfort acceptability band (-1≤TSV≤+1). Even though variations of the indoor temperature were greater than 4.5°C, the comfort level of these buildings did not vary too much.

Correlations between the clothing value, and the indoor operative temperature and outdoor air temperature respectively, were also investigated for both the summer and the winter periods. Similar trends were identified from both correlations, where the correlation between the clothing value and indoor operative temperature was stronger. This research confirmed that people in all three transitional spaces have a similar reaction to different temperatures, i.e. reducing the clothing values as the operative temperature increases, i.e. reducing the clothing values as the operative temperature increases, as compared to other building types [32,41]. It can be explained that people would choose the appropriate clothing according to the outdoor air temperature before they went out. After they entered the space, if they felt thermally uncomfortable, they would adjust their clothing to adapt themselves to the thermal environment in order to make them feel more comfortable.

This statement was supported by the investigations of the open question, which asked about the actions that people would opt to overcome uncomfortable situations. The distributions of the voted actions were similar for the summer and winter periods. Almost 80% of the respondents would take self-adaptive actions, including "adjust clothing" (50% for summer; 53% for winter), "Move / Leave from the uncomfortable location" (21% for summer; 16% for winter), "Drink / Eat" (5% for summer; 6% for winter), and "Do exercise" (2% for summer; 3% for winter), to make themselves warmer or cooler when they felt cool or warm. Therefore, it can be concluded, that in order to maintain an acceptable thermal comfort level in indoor transitional spaces, people would take adaptive actions to make themselves feel comfortable. Similar adaptive actions can also be found in other researches for different indoor environments [35,42–44].

A further analysis was carried out to quantify the acceptable temperatures, in terms of neutral temperature and preferred temperature in the surveyed buildings. Strong correlations were identified for the influences of the indoor operative temperature on people's thermal sensations. Similar trends were identified for the three surveyed buildings where the gradients were all positive. In the other words, the higher the indoor operative temperature, the warmer thermal sensation the building occupants would have [31,35,45]. The average neutral temperatures for all the three surveyed buildings were 20.5°C and 19.5°C, for the summer period and the winter period respectively. This gave an insight of how the thermal environment of a building with transitional spaces should be designed in order to maintain an acceptable thermal comfort level.

Moreover, in order to evaluate the preferred temperatures in the individual surveyed buildings, the intersection point of the "prefer warmer" and "prefer cooler" trends was used to identify the preferred temperatures. The average preferred temperatures identified for all the three surveyed buildings were 21.8°C and 22.3°C, for the summer period and the winter period respectively. It should be noted that the preferred temperature for the NAfW was identified by extrapolation for the winter period, as there was no intersection between the "prefer warmer" and "prefer cooler" trend lines. The average preferred temperatures were 1.3°C and 2.8°C higher than the average neutral temperature for the summer period and the winter period respectively. It reflected that people generally preferred a warmer thermal environment even when they felt thermally comfortable. This may be explained by that people surveyed were situated in a cool climate [38], as the average measured outdoor temperature was lower than 20°C for all surveyed buildings. This probably made people prefer a warmer thermal condition. People may have different preferred temperature than neutral temperature [36–38].

The 80% and 90% acceptable temperature ranges for all the three surveyed buildings were relatively large for both summer and winter periods, with average ranges of 9.6°C and 4.0°C respectively. For the winter period, the average range for the 80% acceptable temperature range of all the three surveyed buildings was 8.3°C, which was brought down to 4.2°C for the 90% acceptable temperature range. This may be explained by the adaptability of the building occupants in the building transitional spaces. In other words, people inside the transitional spaces can still feel thermally comfortable without requiring a fine control of indoor air temperature as they can adapt to the thermal environment by different means such as adjusting clothing and drinking / eating.

The surveyed buildings served different purposes where the people's activity inside the buildings was different. For instance, people visited NAfW for public event such as building tour and exhibition. This led to a relatively higher respondent's activity level when compared to the other two buildings because of a greater number of people were walking or standing before taking the questionnaire surveys. On the other hand, HEB and RWCMD were academic / cultural buildings where more people used the transitional spaces for resting, dining and discussion. This may explain why NAfW had a lower neutral temperature and a wider acceptable temperature range when compared to the other two buildings. From other perspective, different architectural designs of transitional spaces could influence thermal comfort [46–48]. In this study, it explained that this may be due to the different people's usage and activity level within the spaces as a result of architectural designs.

5. Conclusions

The field studies carried out in the transitional spaces of the three surveyed buildings produced an evaluation of the thermal environmental performance and people's adaptability. The majority of the respondents expressed that they experienced a pleasant overall thermal sensation in all the surveyed buildings, in both summer and winter periods. Indoor operative temperature, due to its strong correlation with the thermal sensation vote, was confirmed to be an important factor in determining thermal comfort.

The identified neutral temperatures from the surveyed buildings imply that, in order to maintain an acceptable thermal environment within transitional spaces, the indoor temperature should be 20.5°C and 19.5°C, for the summer period and the winter period respectively. However, a fine temperature control is not necessary because of the fact that the 80% (-1<TSV<+1) and 90% (-0.5<TSV<+0.5) have a relatively wide range of acceptable temperatures. A temperature range of 4°C is considered good enough to maintain an acceptable thermal comfort level within building transitional spaces. The statement is strengthened by the strong correlation between clothing values and indoor operative temperature. Also, by the evaluation of the actions that people would take to overcome uncomfortable situations, where a majority of the people (>80%) would adopt self-adaptive actions such as adjusting clothing, drinking / eating, and moving position to deal with thermal discomfort. In short, people are more prepared to adapt to the environment in preference to attempting to alter the building systems, such as adjusting control of ventilation systems and windows opening.

People surveyed in all the three surveyed buildings tended to have a higher preferred temperature than neutral temperature, in both summer and winter time. This implies, that under Cardiff's weather condition, when the outdoor air temperature is relatively cool, people would prefer a warmer indoor thermal environment. Therefore, the neutral temperature may be considered as a measure of 'lack of discomfort', whilst the preferred temperature is a more positive measure of people's desired comfort level.

On the basis of this research, further research to investigate the impact of the architectural and mechanical system designs on the thermal environment by computational simulations is recommended. Through the simulations, a wider range of environmental conditions and different architectural or system settings can be evaluated and thus means to provide thermal comfort for building transitional spaces can be identified.

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Appendix I

Transitional Spaces Thermal Comfort Questionnaire

Section 1 - PERSONAL INFORMATION

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

Location: ______________________

Time: __________ **Gender:** M / F

Date: __________ **Age:** __________

What are you here for: Working / Dining / Shopping / Resting / Waiting / Other: __________

Are you a regular user of this space (your current location): Yes / No

Have you had any meal during the last hour: Yes / No

Section 2 - THERMAL SENSATION

Please tick the best description about your **current feeling** at this space (your **current location**) using the below scale.

Overall Feeling	Unpleasant	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Pleasant
Comfort Level	Cold	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Hot
Humidity	Dry	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Humid
Air Movement	Still	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Draughty
Your thermal preference	Cooler		☐ -2	☐ -1	☐ 0	☐ 1	☐ 2		Warmer

Section 3 - SUNLIGHT PENETRATION

Your sunlight preference at this space	Less		☐ -2	☐ -1	☐ 0	☐ 1	☐ 2		More

Section 4 - CLOTHING

Please select **ALL** the correct descriptions of what you are **currently** wearing.

Clothings:	Trousers:	Footwear / Accessories:
☐ Short-sleeve shirt (0.15)	☐ Shorts (0.06)	☐ Shoes / Sandals (0.02)
☐ Long-sleeve shirt (0.20/0.30) ☐ thin ☐ thick	☐ Straight trouser (0.15/0.24) ☐ thin ☐ thick	☐ Boots (0.1)
☐ Sleeveless sweater (0.13/0.22) ☐ thin ☐ thick	☐ Sweatpant / Jogger (0.28)	☐ Gloves (0.05)
☐ Long-sleeve sweater (0.20/0.35) ☐ thin ☐ thick	☐ Overalls (0.3)	☐ Socks (0.02/0.03/0.06) ☐ ankle ☐ calf ☐ knee
☐ Jacket (0.25/0.35) ☐ thin ☐ thick	☐ Skirt / dress (0.15/0.24) ☐ thin ☐ thick	Others: __________
☐ Coat / Winter jacket (0.60)	☐ Winter dress (0.33/0.47) ☐ thin ☐ thick	__________

Section 5 - ACTIVITY AT THE CURRENT LOCATION

Please circle the best description of your major activity after you have entered this space (your **current location**).

Sleeping 0.7 Sitting 1.0 Standing 1.2 Walking Normally 2.0 Walking Quickly 2.6

Rushing 3.8 Other: __________

How long you have stayed in this space: ______ hours ______ minutes

Section 6 - PREVIOUS SPACE

Where were you before entering this space: Indoors Outdoors

How long did you stay at the previous space: ______ hours ______ minutes

Comfort Level at the previous space	Cold	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Hot

Section 7 - FEEDBACK / PREVIOUS EXPERIENCE OF THIS SPACE

Any feedback about thermal environment for this space: __________

How would you overcome uncomfortable situation, if any: __________

If you have been to this space before, what is the best thermal description about your previous experience in this space:

Summer Time	Cold	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Hot
Winter Time	Cold	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Hot

- END -

Highlights (for Review)

1. total 1,316 (736 in summer and 580 in winter) valid questionnaires were collected from the building transitional spaces of three different public buildings in Cardiff, UK;
2. indoor operative temperature was well-correlated with thermal sensation votes;
3. acceptable temperature ranges, neutral temperature and preferred temperature were identified;
4. a fine temperature control was unnecessary;
5. people's adaptability to the thermal environment was confirmed;
6. people in cold climate was found to have higher preferred temperature than neutral temperature.