Investigation of Adaptive Thermal Comfort in Building Transitional Spaces - Case Studies in Cardiff, UK

Jason M.Y. Tse[1,2] and Phillip Jones[1]
[1] Welsh School of Architecture, Cardiff University
[2] Ove Arup & Partners International Ltd.

Abstract

Transitional spaces have been widely applied in building designs nowadays, which are present in the form of atria, lobbies, corridors and covered streets. As they have become common features of buildings, they account for 10-40% of the total volume in different types of buildings. However, maintaining an acceptable thermal comfort for transitional spaces poses challenges to building designers and engineers as thermal discomfort has been revealed in such spaces of several newly constructed buildings, where there are still no recommended acceptable comfort range and thermal comfort prediction methods for transitional spaces. This paper aims to evaluate the appropriateness of PMV model in thermal sensation prediction in transitional spaces and to investigate the environmental performance and people's adaptive comfort in transitional spaces. Field studies, which included on-site questionnaire surveys and physical measurements, were carried out during the summer period in three selected case buildings in Cardiff. They were The National Assembly for Wales – Senedd, Hadyn Ellis Building and Royal Welsh College of Music and Drama. The total responses from the questionnaire surveys were 736 for these buildings. This paper first presents the findings from the field studies. Then, comparison between PMV and actual TSV was carried out. Poor correlations between PMV and actual TSV were identified. Besides, in-depth investigations on the human adaptability to thermal environment were conducted. Strong correlations were identified between the clothing value and indoor operative temperature. In addition to the analysis of the open question in the questionnaire about the actions that the people would take to overcome the uncomfortable situations, it is concluded from this research work that fine control of the indoor temperature of transitional spaces is not necessary and people would opt for self-adaptive actions to make themselves feel more comfortable in the transitional spaces.

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

1. Introduction

Transitional spaces can be found in many different kinds of buildings nowadays. Transitional spaces are claimed as "unavoidable spaces in non-domestic buildings", which occupy about 10% - 40% of the total volume in different types of buildings (Pitts & Saleh, 2006). Transitional spaces are defined as the spaces located in-between outdoor and indoor environments, which provide both buffer spaces and physical link (Pitts & Saleh, 2007). Transitional spaces can serve as environmental bridges between the interior and exterior environments and relaxation spaces for the occupants to enjoy the surroundings. In these spaces, the occupants are able to experience the dynamic effects of the external climatic changes. (Taleghani, et al., 2014). Transitional spaces could appear in different forms, including seating area, circulation passage, entrance lobby, cafeteria and meeting places (Ilham, 2006). From the architectural aspect, the transitional spaces can be attached or unattached to a building development (Monterio & Alucci, 2007).

The development of transitional spaces can be traced back to climate sensitive and social use of a central courtyard in ancient design (Li, 2007). Transitional spaces have been used in building design for about 5000 years (Fathy, 1986; Oliver, 2003). Courtyard design in buildings presented the original idea of transitional spaces, which served as a climate modified and central social function space by providing natural ventilation for the internal spaces (Ahmad & Rasdi, 2000). Similar design was found later in 10th to 11th century BC in Chinese residential houses named Siheyuan (Knapp, 2000). Then, later in the 18th century, other central courtyards were found in ancient Roman and Greek houses (Moosavi, et al., 2014), where the term atrium originates from (Hung, 2003). They formed the central room of the building, connecting to all the other chambers (James, et al., 2009). Atrium buildings were popular after the industrial revolution (Saxon, 1983). Over the past decades, because of the advanced technologies such as new materials including glazing and structure and computational modelling (Samant, 2011), transitional spaces have been evolved into different types. Until the present decade, transitional spaces, especially in the form of atrium, have become a dominant feature in built environments (Samant, 2011; Li, 2007).

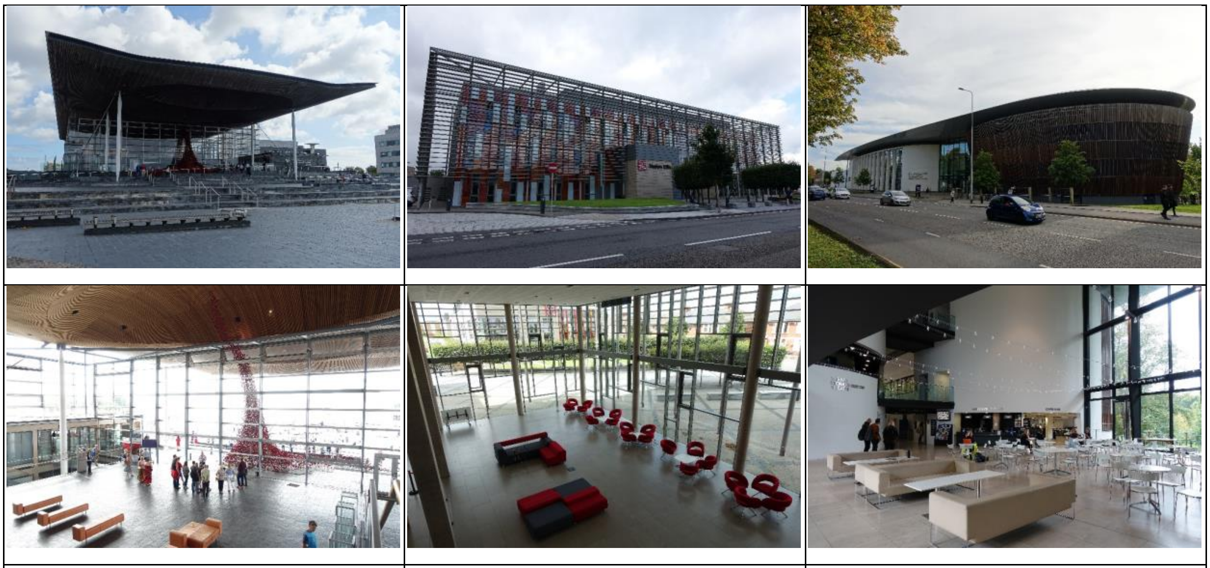
Although transitional spaces do not require fine control of temperature or comfort limits, maintaining an acceptable thermal comfort for such spaces is still a challenge to the building designer (Pitts & Saleh, 2007). Recent researches revealed that the thermal discomfort is a big issue for transitional spaces. Moreover, there is still lack of research evidence on thermal environment of transitional spaces (Monterio & Alucci, 2007; Hui & Jiang, 2014; Rupp, et al., 2015). The majority of previous research on the comfort environment with dynamic states, including transitional spaces like corridors and atria, were conducted in climatic chambers, and only a few of them have been validated through fieldwork studies (Palma, 2015). Most of them just covered human thermal response to stable environment conditions only (Liu, et al., 2014). This may be the reason why transitional spaces are still not clearly addressed in the current comfort standards (van Hoof, 2008), where no recommended acceptable indoor temperature ranges have been specified for thermal comfort in transitional spaces (Yu, et al., 2015).

As to predict thermal comfort within an indoor space, Fanger developed a heat-balance based comfort prediction index in 1972, which was named as Predicted Mean Vote (PMV) (Fanger, 1972). PMV is the most commonly-used thermal comfort index today (Lei, et al., 2017). It is also adopted by the international standards such as ASHRAE (ASHRAE, 2013) and ISO (ISO, 2005) as a basis for comfort evaluation.

This paper therefore aims to evaluate the appropriateness of PMV model for thermal sensation prediction in transitional spaces and to investigate the environmental performance and people's adaptive comfort in transitional spaces by conducting field studies which include on-site questionnaire surveys and physical measurements in three case buildings in Cardiff.

2. Research Methodology

The methodology adopted in this research included on-site questionnaire surveys and physical measurements in three existing buildings in Cardiff – The National Assembly for Wales – Senedd (NAfW), Hadyn Ellis Building (HEB) and Royal Welsh College of Music and Drama (RWCMD), as shown in Figure 1. Prior to the confirmation of the proposed methodology for the main studies in these three buildings, a pilot study had been performed in Optometry Building of Cardiff University on 21st July 2017. The study was thoroughly reviewed, including the feedbacks that were obtained during the pilot study. The proposed methodology was then optimised before carrying out the main studies. During the field studies, the indoor and outdoor environmental conditions were monitored at the same time when the questionnaire surveys were carried out.



NAfW | HEB | RWCMD

Figure 1. Surveyed buildings and their indoor environments

2.1 Surveyed Buildings

The selected buildings were located in different locations in Cardiff, where the distance from the outdoor weather station was ranged from 0.1km to 2.8km. The function of these buildings was quite different but they were all open to the public during their opening hours. The windows were designed to be automatically opened through the control from Building Management System (BMS) to enhance the ventilation during warm days so that a more desirable thermal comfort level could be maintained within the buildings. In each of the selected buildings, 3 days in the summer period were spent to carry out the field studies, which included questionnaire surveys and physical measurements. 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
Distance from weather station	2.8km	0.6km	0.1km
Survey dates	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 period	10:30 – 16:30	08:30 – 17:30	08:30 – 19:00

2.2 Physical Measurements

At the same time when the questionnaire survey was carried out, the indoor environmental parameters including air temperature, relative humidity, air velocity and black globe temperature were monitored. The accuracy of the instrumentations used for the field studies complied with the requirements of ASHRAE 55-2013 (ASHRAE, 2013). Table 2 summarises the details of the instrumentations that were used in the field studies. Measurements covered the indoor transitional spaces including entrance lobby, atrium and café area. In order to ensure the readings were representative throughout the surveyed area, measurements had been taken in different locations within a space to identify the best measurement location. The air speed was measured at 15-minute intervals and all the other parameters were monitored at 1-minute intervals. The measurement locations were set at 1.1m height from the floor. For the outdoor environmental parameters, data were recorded every 5 minutes by a weather station which was installed on the rooftop of the Bute Building, the Architectural School of Cardiff University. The model of the weather station was Campbell Instruments CR10 data logger. The air temperature and relative humidity were measured by Rotronic temperature and humidity probe in a radiation shield.

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

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. 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 adopted for the thermal sensation questions and thermal and sunlight preference questions respectively, as presented in Table 3. Besides, in order to understand the people’s adaptability to thermal environment, an open question “how would you overcome uncomfortable situations, if any” was designed in the questionnaire. Additional data collected from the questionnaire included the demographic data, activity level, clothing insulation, time spent in interviewed location, previous space locations and time spent in previous space and feedbacks and previous thermal experience in the interviewed location. Building users were randomly selected within the transitional spaces of the surveyed buildings to carry out the questionnaire survey.

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 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 significance level of the analysis was all set to be 0.05. In other words, the results were statistically significant when p-value < 0.05.

3. Results and Analysis

3.1 Descriptive Analysis

Throughout the summer period, the total number of responses collected from the questionnaire surveys were 736, where 282, 207 and 247 surveys were contributed by 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.

For NAfW, it is a government building that is open to the public. Because a special event "Poppies – weeping window" was held during the surveyed period, a significant number of respondents from the survey were visitors to the building. Guided tours were taking place regularly at the atrium space on the Ground Floor at designated times. The major purpose of most of the visitors who stayed in the atrium was just for the tours and thus lesser responses could be collected from the atrium space. By contrast, majority of responses were collected from the exhibition area and café area on the First Floor. The average activity level of the respondents is higher than the other two surveyed buildings owing to a larger portion of people who walked or stood to watch the exhibition or appreciate the building architectural design or functional use of different parts of the building. Although the outdoor temperature monitored during the questionnaire survey was highest among all the surveyed buildings, the measured indoor temperature was the lowest. It can be explained by the natural ventilation of the building. During the surveyed period of time, the windows were opened to keep the building ventilated.

HEB is an institutional research building that provides facilities such as offices, laboratories, meeting spaces, seminar and lecture rooms for university students or researchers to carry out 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 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, more respondents' major activity in the transitional spaces was sitting when compared to NAfW. Therefore, the average activity level was lower than NAfW. During the survey period, the windows were closed most of the time. In some occasions when the temperature rose up, the windows were opened to adopt natural ventilation.

For RWCMD, as the academic term started when the questionnaire survey was carried out, even more respondents were undergraduate and postgraduate students when compared to HEB. Therefore, the average age of respondents from RWCMD was the lowest among all the surveyed buildings. As there were a great number of chairs and tables provided for the building users in the atrium space and café area under study, the average activity level of the respondents was lowest when compared to the other two surveyed buildings, where the respondents were mainly sitting. During the survey period, the windows were closed all the time. This may explain why the average monitored indoor temperature was higher than the other buildings.

Table 4. Summary of the surveyed and monitored results

		NAfW	**HEB**	**RWCMD**
Total responses (N)		282	207	247
Male respondents		110 (39%)	81 (39%)	115 (47%)
Female respondents		172 (61%)	126 (61%)	132 (53%)
Age	Mean	42	32	26
	SD	18	10	10
Clothing value (clo)	Mean	0.50	0.60	0.60
	SD	0.17	0.20	0.20
Activity level (met)	Mean	1.44	1.30	1.18
	SD	0.48	0.47	0.46
Outdoor temperature (°C)	Mean	18.14	16.62	16.41
	SD	2.30	1.84	1.33
Indoor temperature (°C)	Mean	20.85	22.76	22.93
	SD	1.32	0.99	0.92
Relative humidity (%)	Mean	43.60	45.30	57.26
	SD	5.26	9.32	6.79

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

Figure 2 illustrates the frequency distribution chart of the thermal sensation votes (TSV) that were collected from questionnaire surveys in the three surveyed buildings – NAfW, HEB and RWCMD. The thermal sensation distribution was similar among the 3 surveyed buildings, where the majority of respondents voted "neutral" for the thermal comfort and the others tended to have feeling at warmer side. About 85%, 83% and 76% of the respondents were found in the 80% acceptability comfort band (-1≤TSV≤+1), as defined by ISO 7730:2005 (ISO, 2005), for NAfW, HEB and RWCMD respectively. In addition, for the question about overall thermal feeling of the building, about 94%, 82% and 91% of the respondents felt pleasant (i.e. voted for 1 or higher) for NAfW, HEB and RWCMD respectively. The average vote for the overall thermal feeling for NAfW (mean: 2.25; SD: 0.96) is higher than that for HEB (mean: 1.58; SD: 1.27) and RWCMD (mean: 1.89; SD: 1.08). In order words, the thermal environment of all the 3 surveyed buildings made people feel comfortable in the transitional spaces.

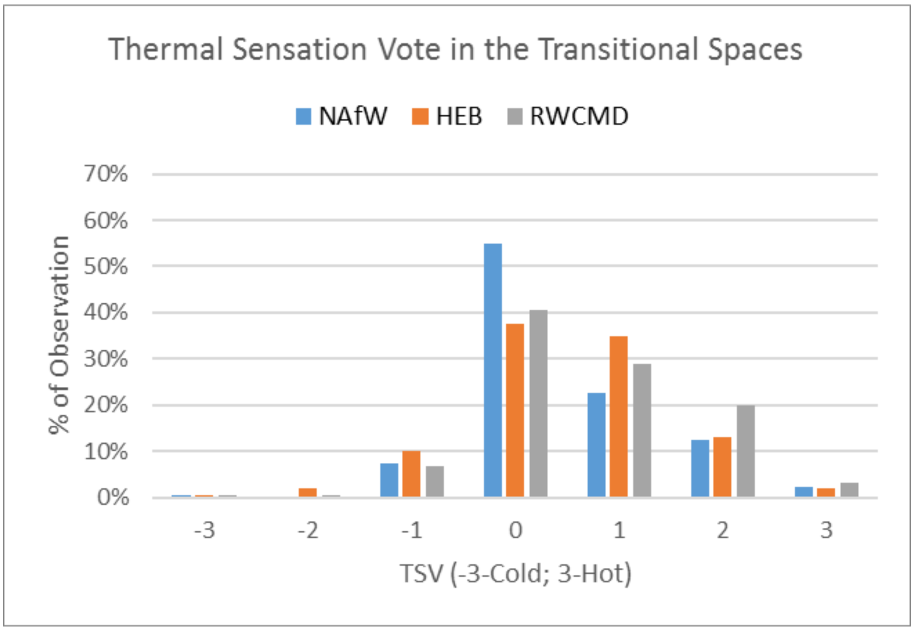


Figure 2. Frequency distribution of thermal sensation votes (TSV) in different transitional spaces

3.2 Correlation Analysis

Pearson (2-tailed) correlation analysis was conducted to evaluate the correlation between different parameters and clothing value, where the results are summarised in Table 5. It was found that clothing value correlated better with indoor operative temperature than with outdoor temperature. The relationship was stronger for NAfW than for the other 2 surveyed buildings. Furthermore, the correlation between clothing value and indoor operative temperature was the best for NAfW ($p<0.01$), while that for the HEB and RWCMD were weaker but were still statistically significant ($p<0.05$).

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

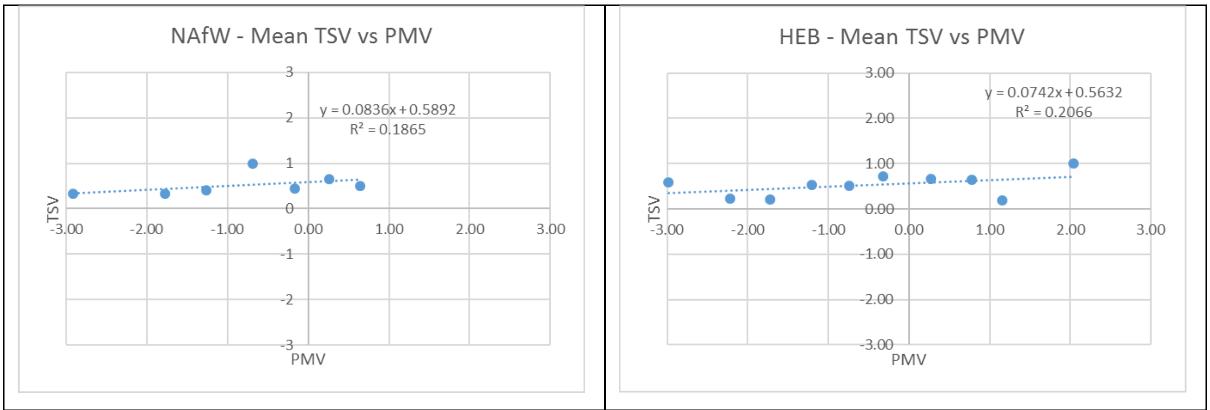
	Clothing Value		
	NAfW	HEB	RWCMD
Indoor Operative Temperature	-0.384**	-0.260*	-0.145*
Outdoor Temperature	-0.386**	-0.072	-0.107

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

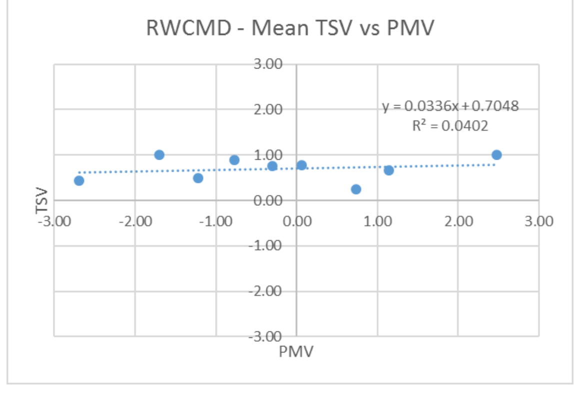
3.3 Evaluation of Prediction Accuracy of Thermal Comfort Level in Transitional Spaces using PMV Model

PMV, the widely-adopted thermal comfort prediction model for indoor environments (Humphreys & Nicol, 2004), was applied to the field studies in this research in order to evaluate if it is an appropriate model for indoor transitional spaces. Based on the monitored and surveyed results, PMV was calculated and plotted against the actual thermal sensation vote (TSV) to test the relationship between these two values for each of the surveyed buildings. The results are illustrated in Figure 3. The correlations between the PMV and the mean TSV were not strong, which were ranged from 0.0402 to 0.2066 and the gradients varied from case to case. In short, PMV is not an appropriate model that can accurately predict thermal sensation in transitional spaces. Taking NAfW as an instance, for the PMV ranged between -3, the actual

TSV reported was around 0.35, where the difference between the actual TSV and the predicted one was 3.35. From the other point of view, the average PMV calculated for the NAfW, HEB and RWCMD were -1.35, -0.62 and -0.58 respectively, while the average actual TSV for these buildings were 0.45, 0.51 and 0.69 respectively. The deficiency between the average values of PMV and TSV ranged from 1.13 to 1.80.



NAfW **HEB**



RWCMD

Figure 3. Evaluation of Thermal Comfort Prediction using PMV

3.4 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 (ASHRAE, 2013) and ISO 7703:2005 (ISO, 2005). In order to reduce the impact of outliers in the database, binning method was adopted by taking the weighted averages for the sample size within every half-degree-Celsius bin. Figure 4 illustrates the linear regression plots between the average clothing value and the indoor operative temperature and outdoor temperature respectively.

For the correlation of clothing value against indoor operative temperature, the linear relationship was strong, with the 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, just that the correlation was weaker than the comparison against indoor operative temperature. The coefficient of determination (r2) was ranged from 0.23 to 0.41. The identified gradients were the same, which were negative, as the correlations against indoor operative temperature.

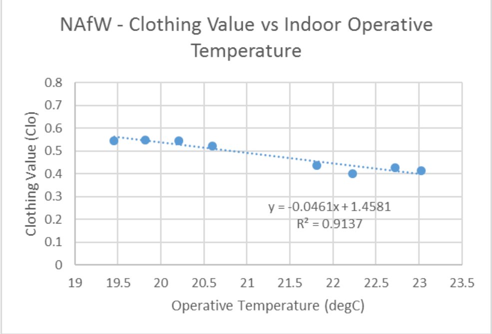
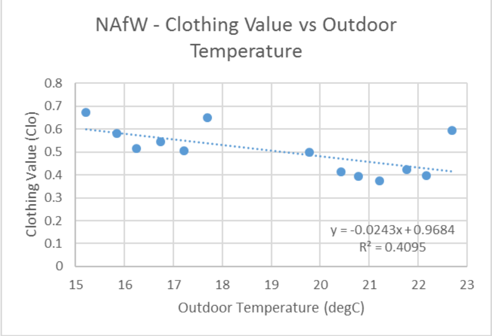
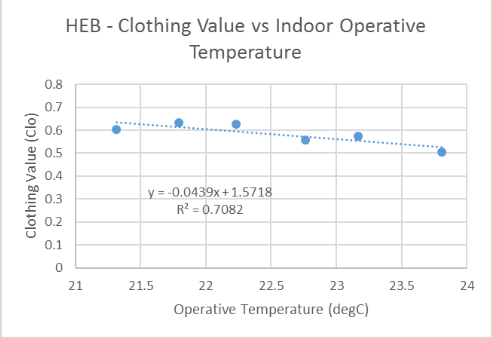
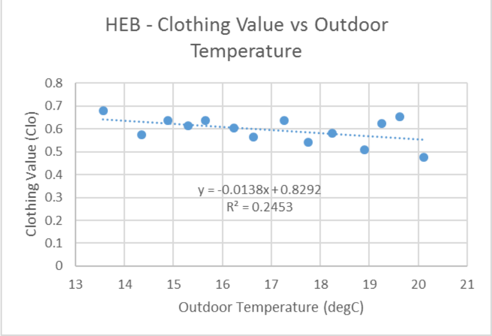
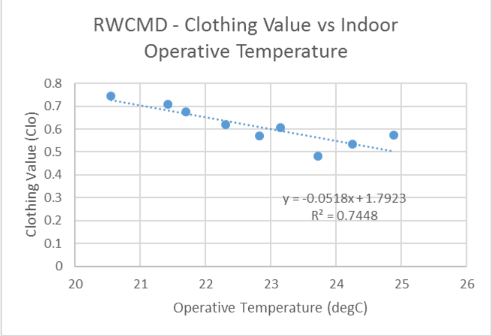
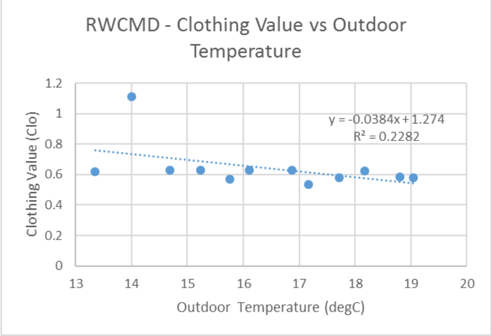
Surveyed Buildings	**Clothing Value**	
	vs Indoor Operative Temperature	**vs Outdoor Temperature**
NAfW		
HEB		
RWCMD		

Figure 4. Influence of indoor operative temperature and outdoor temperature on clothing value

3.5 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. Out of 736 surveyed questionnaires in total for the 3 surveyed buildings, the response rate for this question was 320, or 43.5%. Some of the people gave more than one answer. 339 answers collected from the respondents. As it was an open question, the use of words was different from different answers but they can basically be grouped into 8 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" 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"; and rare answers such as "talk my way through" and "more light" are classified as "other". Table 6 summarises the details about the actions that respondents would take to overcome uncomfortable situations.

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 tend to adapt themselves to the thermal environment to make themselves feel more thermally comfortable rather than approaching to change the building operations.

Table 6. Summary of respondents' actions to overcome uncomfortable situations

Categorised actions to overcome uncomfortable situations	NAfW	HEB	RWCMD	Total
Adjust clothing	55 (54%)	43 (44%)	71 (50%)	**169 (50%)**
Move / Leave from the uncomfortable location	23 (23%)	14 (14%)	35 (25%)	**72 (21%)**
Use mechanical means	11 (11%)	12 (12%)	11 (8%)	**34 (10%)**
Close the openings	1 (1%)	16 (16%)	6(4%)	**23 (7%)**
Drink / Eat	4 (4%)	4 (4%)	10 (7%)	**18 (5%)**
Other	2 (2%)	4 (4%)	6 (4%)	**12 (4%)**
Report to building staff	2 (2%)	3 (3%)	1 (0%)	**6 (2%)**
Do exercise	3 (3%)	2 (2%)	0 (0%)	**5 (2%)**
Total response rate	**101 (30%)**	**98 (29%)**	**140 (41%)**	**339**

4. Discussions

The correlation between PMV and actual TSV showed that PMV model was not an appropriate one to predict the thermal sensation in transitional spaces. This is not a surprising finding because it was known that PMV model was originally intended for application in spaces that are air-conditioned and well climatically-controlled (van Hoof, 2008). In addition, this can be explained that the transitional spaces under study were not air-conditioned during the survey period and the people had a variety of activity levels in the spaces.

Besides, the data analysis showed that the thermal comfort level was highly acceptable by the building users, with very high percentage of respondents (>82%) voting the overall thermal feeling as "pleasant" (> +1 vote) in all the 3 surveyed buildings. Moreover, more than 80% of the respondents voted the TSV within the 80% comfort acceptability band ($-1 \leq TSV \leq +1$). 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. Similar trends were identified from both correlations, where the correlation between the clothing value and indoor operative temperature was stronger. It can be explained that people would choose the appropriate clothing according to the outdoor air temperature before they went out. By then, after they entered the space where they felt thermally uncomfortable, they would adjust their clothing to adapt themselves to the thermal environment to make them feel more comfortable.

This statement was supported by the investigations of the actions that the people would opt to take to overcome uncomfortable situations. Almost 80% of the respondents who answered this open question would take self-adaptive actions, including "adjust clothing" (50%), "Move / Leave from the uncomfortable location" (21%), "Drink / Eat" (5%), and "Do exercise" (2%), to keep themselves warmer or cooler when they felt cool or warm. Therefore, it can be concluded from this research study that in order to maintain an acceptable thermal comfort level in indoor transitional spaces, people would act to adapt to the thermal environment to make themselves feel comfortable and thus fine control of indoor temperature is not necessary for transitional spaces.

5. Conclusions

This work investigated the environmental performance of building transitional spaces by conducting field studies, including questionnaire surveys and physical measurements, in three different buildings in Cardiff, which were The National Assembly for Wales – Senedd, Hadyn Ellis Building and Royal Welsh College of Music and Drama during the summer period in 2017. Total responses of 736 from the building occupants were collected and analysed.

Poor correlation was identified between PMV and actual TSV that were obtained from the questionnaire surveys. PMV model was therefore proven to be an inappropriate thermal model for predicting thermal sensation in transitional spaces. It could be explained that the transitional spaces under study were not air-conditioned and the people using such spaces had a variety of activity levels.

A vast majority of the respondents from the surveyed buildings expressed pleasant overall thermal feeling with the environment in transitional spaces. Although there was slight difference in a number of factors such as age, activity level, indoor temperature and clothing values, similar thermal sensation vote was identified, where 76% - 83% of the respondents voted within a comfort acceptance band (±1 sensation) for these surveyed buildings. Further investigations were carried out to evaluate the human thermal adaptability by correlating the reported clothing value against indoor operative temperature and outdoor temperature respectively. Linear relationships were found for both comparisons, where the correlation was much stronger for the impacts of indoor operative temperature on clothing value.

In addition, actions that people would take to overcome uncomfortable situations were also investigated. The answers from the respondents were grouped into 8 categories, which were "adjust clothing", "drink/eat", "move/leave from the uncomfortable location", "do exercise", "use mechanical means", "report to building staff", "close the openings" and "other". The first four categories were treated as self-adaptive actions. Nearly 80% of the respondents opted for self-adaptive actions to overcome uncomfortable situation. This further explained the strong correlation between clothing value and indoor operative temperature. The higher the operative temperature, the less clothing value was reported in the questionnaire surveys. In other words, people would tend to wear less when the indoor operative temperature rose, or vice versa. Understanding the human adaptability to its thermal environment, fine control of indoor temperature is not necessary for maintain acceptable thermal comfort in transitional spaces. On the basis of this research, further research works on quantifying the comfort temperature range and methods to provide all-year-round comfortable environment in transitional spaces are recommended.

Acknowledgement

The authors would like to express our gratitude to the National Assembly for Wales – Senedd, Hadyn Ellis Building and Royal Welsh School of Music and Drama for the great support to the research work. Not only did they lend the spaces for the field studies, their building management teams also provided great technical assistance for the data collections and measurement setups.

References

Ahmad, M. H. & Rasdi, M. T. H. M., 2000. *Design Principles of Atrium Buildings for the Tropics.* Malaysia: Penerbit UTM.

ASHRAE, 2013. *ANSI/ASHRAE Standard 55 - Thermal Environmental Conditions for Human Occupancy.* Atlanda: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Cheng, V., Ng, E., Chan, C. & Givoni, B., 2010. Outdoor thermal comfort study in sub-tropical climate: A longitudinal study based in Hong Kong. *International Journal of Biometeorology,* 56(1), pp. 43-56.

Chun, C., Kwok, A. & Tamurac, A., 2004. Thermal comfort in transitional spaces—basic concepts: literature review and trial measurement. *Building and Environment,* Issue 39, pp. 1187-1192.

Fanger, P., 1972. *Thermal Comfort.* New York, USA: McGraw Hill.

Fathy, H., 1986. *Natural energy and vernacular architecture: principles and examples with reference to hot arid climates.* Chicago: The University of Chicago Press.

Grifoni, R. C., Passerini, G. & Pierantozzi, M., 2013. Assessment of outdoor thermal comfort and its relation to urban geometry. *Sustainable Development and Planning,* Volume VI, pp. 3-14.

Hui, S. C. M. & Jiang, J., 2014. *Assessment of thermal comfort in transitional spaces.* Hong Kong, Kowloon Shangri-la Hotel, Tsim Sha Tsui East, Kowloon.

Humphreys, M. & Nicol, J., 2004. Do people like to feel “neutral”? Response to the ASHRAE scale of subjective warmth in relation to thermal preference, indoor and outdoor temperature.. *ASHRAE Transactions,* 110(2), p. 569–577.

Hung, W. Y., 2003. Architectural Aspects of Atrium. *International Journal on Engineering Performance-Based Fire Cordes,* 5(4), pp. 131-137.

Ilham, S., 2006. *Thermal comfort in transitional spaces in desert communities: the study of cases in Tucson, Arizona,* Tucson: The University of Arizona.

ISO, 2005. *ISO 7730, Ergonomics of the Thermal Environment—Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria.* Geneva: International Standard Organization.

James, P., Jentsch, M. & Bahaj, A., 2009. Quantifying the added value of BiPV as a shading solution in atria. *Solar Energy,* Volume 83, pp. 220-231.

Knapp, R. G., 2000. *China’s Old Dwellings.* Honolulu: University of Hawaii Press.

Lei, Z., Liu, C., LiWang & Li, N., 2017. Effect of natural ventilation on indoor air quality and thermal comfort in dormitory during winter. *Building and Environment,* Volume 125, pp. 240-247.

Li, R., 2007. *PhD Thesis: Natural ventilation of atrium spaces,* Sheffield, UK: School of Architecture, The University of Sheffield.

Liu, H. et al., 2014. The response of human thermal perception and skin temperature to step-change transient thermal environments. *Building and Environment,* March, Volume 73, pp. 232-238.

Matzarakis, A. & Mayer, H., 1997. Heat stress in Greece. *International Journal of Biometeorology,* Volume 41, pp. 34-39.

Monterio, L. M. & Alucci, M. P., 2007. *Transitional spaces in São Paulo, Brazil: Mathematical modeling and empirical calubration for thermal comfort assessment.* Beijing, Building Performance Simulation Association Conference and Exhibition.

Moosavi, L., Mahyuddin, N., Ghafar, N. A. & Ismail, M. A., 2014. Thermal performance of atria: An overview of natural ventilation effective designs. *Renewable and Sustainable Energy Reviews,* Volume 34, pp. 654-670.

Nikolopoulou, M., Baker, N. & Steemers, K., 2001. Thermal comfort in outdoor urban spaces: understanding the human parameter. *Solar Energy* , Volume 70, pp. 227-235.

Oliver, P., 2003. *Dwellings: the house across the world.* Oxford: Phaidon Press Ltd..

Palma, G. A. V., 2015. *Short-term thermal history in transitional lobby spaces,* Sheffield: The University of Sheffield.

Pitts, A. & Saleh, J. B., 2006. *Transition Spaces and Thermal Comfort – Opportunities for Optimising Energy Use.* Geneva, PLEA2006 - The 23rd Conference on Passive and Low Energy Architecture.

Pitts, A. & Saleh, J. B., 2007. Potential for energy saving in building transition spaces. *Energy and Buildings,* pp. 815-822.

Rupp, R. F., Vasquez, N. G. & Lamberts, R., 2015. A review of human thermal comfort in the built environment. *Energy and Buildings,* Volume 105, pp. 178-205.

Samant, S., 2011. *PhD Thesis: A parametric investigation of the influence of atrium facades on the daylight performance of atrium buildings,* Nottingham, UK: University of Nottingham.

Saxon, R., 1983. *Atrium Building: Development and Design.* 2nd Edition ed. London: Architectural Press.

Taleghani, M., Tenpierik, M. & Dobbelsteen, A., 2014. Energy performance and thermal comfort of courtyard/atrium dwellings in the Netherlands in the light of climate change. *Renewable Energy,* Volume 63, pp. 486-497.

Thorsson, S., Lindqvist, M. & Lindqvist, S., 2004. Thermal bioclimatic conditions and patterns of behaviour in an urban park in Göteborg, Sweden. *International Journal of Biometeorology,* Volume 48, pp. 149-156.

van Hoof, J., 2008. Forty years of Fanger's model of thermal comfort: comfort for all?. *Indoor Air,* Volume 18, pp. 182-201.

Vu, T., Asaeda, T. & Eusuf, M., 1998. Reductions in air conditioning energy caused by a nearby park. *Energy and Buildings,* Volume 29, pp. 83-92.

Yu, Z., Yang, B. & Zhu, N., 2015. Effect of thermal transient on human thermal comfort in temporarily occupied space in winter - A case study in Tianjin. *Building and Environment,* Volume 93, pp. 27-33.