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Thermal Comfort in Semi-Outdoor Studying Spaces: A case study of Universiti Sains Malaysia

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Abstract. The paper presents an assessment of thermal conditions within semi-outdoor spaces used for the activity of studying. It aims to observe the potential of this type of spaces for human activities as a replacement or complementary to air-conditioned indoor spaces in order to reduce the energy consumption. The field work research, consisting of meteorological measurements alongside a questionnaire survey, was conducted in three studying areas at Universiti Sains Malaysia. The results demonstrate that under certain conditions, thermal comfort is achievable in studying semi-outdoor spaces. Further, the significance of objective and subjective factors in shaping users' thermal comfort perception is discussed.

1. Introduction

Building sector is witnessing a mechanization increase and rising of energy consumption. In tropical countries such as Malaysia, air-conditioning system becomes the primary consumption for occupants' thermal comfort. This problem is largely linked to the current approach of comfort that is based on the heat balance model. As a result of adopting this model, thermal comfort is specified within a narrow range, which is usually difficult to achieve without air-conditioning. Consequently, it promotes unsustainable extensive use of these systems. Because of that, current thermal comfort approach is one of the most controversial subjects in the field of building science [1]. Within the heat balance model, comfort is provided to the passive recipient occupant of the space. Comfort is defined by six factors affecting the thermal balance between the human body and his environment. Four factors are environmental (air temperature, mean radiant temperature, air velocity and relative humidity) and two are personal (metabolic rate and clothing insulation) [2].

The alternative view of comfort is the adaptive approach. Its principle contends that in the case of discomfort, people will act to restore their comfort. The occupant is considered more than a passive recipient of the thermal conditions. He rather plays an active role to achieve his comfort [3]. In this approach, comfort depends on the abovementioned factors in addition to other personal ones that dictate the different adaptation processes. These processes are categorised as follows: physiological adaptation (acclimatisation); behavioural adaptation (clothing change, changes in the activity level or taking hot or cold drinks, changing of position or posture, or moving to another place, etc.); and psychological adaptation (experience, expectations, time of exposure, perceived control, naturalness, environmental stimulation). This adaptive approach allows a much wider thermal comfort range compared to the heat balance model. Such a distinction opens opportunities to take advantage of non-mechanical solutions to create comfortable environments. One of these opportunities is the reengagement with the outdoor and

softening the barriers between indoor and outdoor [4, 5]. In this connection, semi-outdoor spaces could play such a role. They are defined as spaces open to the outdoor while still not open to the sky [6].

The literature shows that the semi-outdoor spaces have potential for energy saving. They could be utilized as buffer zones and transitional spaces that offer time for thermal adjustment. These spaces could also provide a more comfortable conditions in contrast to the outdoors allowing interactions and engagement in certain activities. The energy demand, therefore, will be reduced as people spend less time indoors. The literature has mainly investigated thermal comfort in semi-outdoors being used for recreational activities, temporary activities or transitional spaces, including lobbies, balconies, pavilions, stations, etc. Nevertheless, few studies have shown that under the adaptive comfort approach, thermal comfort is achievable in semi-outdoor spaces—particularly in the tropical region— if some elements like shading and good air movement are taken into consideration [7, 8].

Based on these previous findings, the current paper aims to further assess thermal comfort in semi-outdoors used for a long-term activity usually held indoors, then examine the different factors affecting it. By playing the role of an alternative or complimentary space to a mechanically controlled indoor environment, a conclusion of whether these spaces may reduce energy consumption could be drawn. The activity of studying is selected as a case study. Besides the possibility of energy savings, using semi-outdoors settings for studying can be very beneficial to the learning process [9].

2. Materials and method
This study adopts a quantitative approach based on micro-climate field measurements alongside a transverse questionnaire.

2.1. Study location
The field work is conducted at Universiti Sains Malaysia, in Penang, Malaysia. Within USM campus—based on attendance rate and physical characteristics—two semi-outdoor spaces used for studying have been selected. These are the semi-outdoor reading area of the library (Code: L2) and the dining hall of RESTU and SAUJANA hostels (Code: L3). L2 is an open, naturally ventilated space, whereas L3 is an open space with mechanically aided ventilation using ceiling fans. Additionally, a third space, the 24-hour reading room, an air-conditioned indoor space, is selected as a reference for comparison (figure 1).

2.2. Collected data
A number of thermal indices can be employed to evaluate thermal comfort. For outdoor and semi-outdoor studies, the physiological equivalent temperature (PET) is considered to be the most suitable. In order to calculate PET, RayMan software version 1.2 is used, which requires the input of six parameters: air temperature (T_a); humidity (RH); air velocity (V_a); mean radiant temperature (T_{mrt}); activity level (Met); clothing insulation (I_{cl}). The first three parameters are recorded automatically on-site using a microclimatic station, which is composed of two data loggers connected to the different sensors, all mounted on a 1 m height tripod (figure 1). T_{mrt} is calculated based on measurements of globe temperature (T_g). In order to measure T_g, a globe thermometer have been created using a (Pt100) temperature sensor, positioned in the centre of a 40mm acrylic ping pong ball painted flat grey (RAL7001) [10]. Met is set to 58.2 W/m2 for reading and writing activity. I_{cl} is calculated for each respondent based on his/her clothing items.

The questionnaire consists of three sections. The first collects respondents' demographic information, the second concerns subjects' perception of comfort level and the third section examines the influence of different objective and personal factors on comfort.

Figure 1. Locations and instruments. (L1) 24-hour reading room. (L2) Semi-outdoor reading area of the library. (L3) Dining hall of RESTU and SAUJANA hostels. (a) air velocity . (b) air temperature and humidity . (c) globe temperature. (d & e) data logger.

2.3. *Procedure*
The study was conducted at the end of a February month over a period of 5 days, with 15 hours surveyed each day (8 a.m. to 23 p.m.), according to the following procedure: While the measurements are collected automatically with a sampling rate of 5 minutes, the arrival time to the surveyed area of every person is noted, then after 15 minutes—allowing adjustment to the space conditions [11]—the subject is approached for participation. Following these steps, every user of the space is approached, except people staying less than 15 minutes and those using the space for activities other than studying. At the end, 348 questionnaires have been collected to be analysed and compared to the measured parameters.

3. Results and discussion

3.1. *Thermal comfort state*
The highest thermal comfort votes are observed among the occupants of semi-outdoor reading area (L2), followed by the 24-hour reading room (L1) then the dining hall (L3) (figure 2). 82.6%, 79.1% and 57.1% of occupants' votes are within "neutral" to "very comfortable" range, corresponding to (M=0.70, SD=1.29), (M=0.63, SD=1.32) and (M=-0.32, SD=1.12) in L2, L1 and L3 respectively. Furthermore, it is observed that in the case of L2, comfort level is even better than in the air-conditioned indoor space. In what follows, we will explore the different factors that have led to these results.
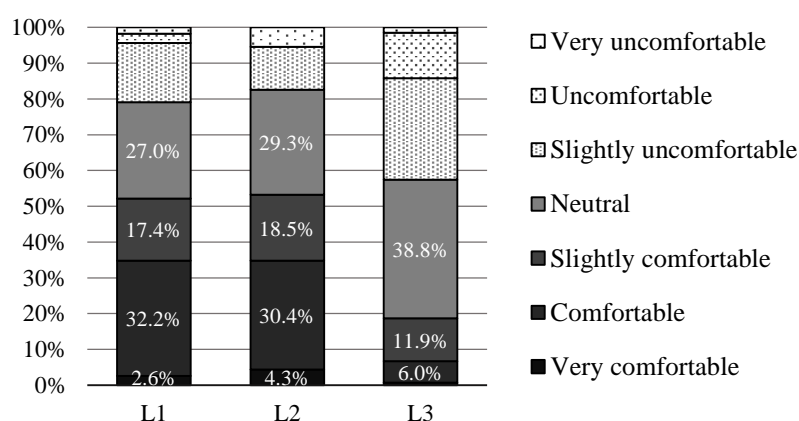
Figure 2. Thermal comfort votes in the three surveyed locations.

3.2. *Environmental factors*

3.2.1. Air temperature (Ta). The recordings show that the lowest air temperatures are measured in L1 (M=21.41 °C, SD=1.28), where the temperature has varied between 19.42 and 23.25 °C. The semi-outdoor L3 (M=30.55 °C, SD=1.81) occupies the second place with a wider variation range (26.92–

33.88 °C). Lastly, L2 (M=31.01 °C, SD=2.19) with temperatures varying from 26.42 °C to 34.16 °C (figure 3). These results do not exactly match the respondents' temperature perceptions, where on a scale from "Cold" (-3) to "Hot" (+3), L1 is perceived to have the lowest temperature (M=-1.10, SD=1.09), followed by L2 (M=0.17, SD=1.23) then L3 (M=0.96, SD=1.29). Moreover, thermal satisfaction that corresponds to the thermal sensation votes (TSV) within the range "slightly cool" (-1) to "slightly warm" (+1), is higher in the semi-outdoors L2 (72.8%) and L3 (65.7%) compared to the indoor L1 (62.6%). By juxtaposing these results with thermal comfort votes, it is clear that the latter correspond better with the perceived temperature rather than the measured. This is confirmed by the correlation tests (table 1).

3.2.2. Relative humidity (RH). The recorded relative humidity is approximately constant in L1 (45–50%). However, in L2 and L3, humidity varies following the opposite direction of air temperature, with (36–63%) in L2 and (42–73%) in L3. Furthermore, the votes regarding humidity, on the seven-point scale ranging from "Much too dry" (-3) to "Much too humid" (+3), are mostly within the "just right" category. That is 61.7% of L1 users, 60.9% in L2 and 41.4% in L3. The rest of the votes are concentrated on the dry side of the scale i.e. (M=-0.23, SD=0.74) in L1, (M=-0.32, SD=0.73) in L2 and (M=-0.26, SD=1.16) in L3.

A correlation of data shows that a significant relationship exists between *RH* and thermal comfort votes in the studied semi-outdoors. High *RH* levels are associated with low comfort levels. In contrast, humidity perception is not significantly related to comfort level (table 1). According to Metje, Sterling and Baker [12], this insignificance is due to peoples' inability to realise the effect of humidity unless it is very high or very low.

3.2.3. Air velocity (V_a). The highest levels are registered in L2 (M=0.82 m/s, SD=0.51) followed by L3 (M=0.44 m/s, SD=0.13) then L1 with low and stable levels (M=0.11 m/s, SD=0.04). The maximum air velocity is recorded in the semi-outdoor L2, which has the value of 1.86 m/s (figure 3). These results are in accordance with respondents' evaluations, where air velocity is perceived to be on the breezy side of the scale in L2 (M=0.40, SD=0.85). On the other hand, the conditions tend toward the still side in L1 (M=-0.31, SD=0.82) and L3 (M=-0.17, SD=0.99). In addition, a preference of "more" air movement in the semi-outdoor spaces is observed, especially in L3 where 64.2% of users want "more" air-movement compared to 57.6% in L2. In L1, the majority (50.9%) are content with the situation and want "no change".

The correlations (table 1) demonstrate that both measured and perceived air-velocity are significantly related to thermal comfort votes. Higher air velocity is associated with better thermal comfort levels.

3.2.4. Radiant temperature (T_{mrt}). The mean radiant temperature does not significantly differ from air temperature. In the semi-outdoor spaces, the difference between the averages is 0.38 °C. The most noticeable difference is during the afternoon period where T_{mrt} is a bit higher. In the indoor space T_{mrt} is higher than T_a throughout the day, with an averaged difference of 0.89 °C. The seemingly small difference between T_a and T_{mrt} could be explained by the absence of direct sun exposure, which minimises the radiant temperature exchange. Regarding solar radiation perception, on a seven-point scale ranging from "very weak" (-3) to "Very strong" (+3), the votes tend toward the "strong" side of the scale in L3 (M=1.08, SD=1.31) and L2 (M=0.65, SD=1.19). In the indoor space L1, however, the votes tend toward the "weak" side (M=-0.14, SD=1.43). Furthermore, regarding preferences—except for the "no change" category that is chosen by 50%, 46.2% and 36% of L1, L2 and L3 occupants—the other categories ("more" and "less" sun) are balanced to a certain degree. This is most probably due to users' different exposures (i.e. users on the perimeter are more exposed than those in the centre of the space).

In relation to thermal comfort votes, it is found that the measured *Tmrt* does not significantly correlate (table 1). Contrariwise, users' perception of solar radiation is significantly related to comfort level.

3.2.5.Physiological equivalent temperature (PET). In the semi-outdoor spaces, *PET* varies between 24 and 34 °C (figure 3), with a neutral value of 27.4 °C (figure 4). Neutral *PET* is calculated for thermal sensation votes between (-1) and (+1) based on the method described in Lin and Matzarakis [13]. *PET* variation is generally close to T_a or a bit higher. However, during the morning period in L2—as a consequence of high air velocity—*PET* is much lower than T_a, where the difference reached a maximum of 2.59 °C.

The calculated *PET* is compared to thermal comfort ranges of Western/Middle Europe (18–23 °C), and sub-tropical Taiwan (26–30 °C) [13]. In the first comparison, despite *PET* laying outside the comfort range, the current study shows that comfort level is high in the thermally better space L2. It clarifies that occupants of the studied spaces are more tolerant to higher temperatures compared to the European study. This indicates that adaptation is taking place. The second comparison shows that despite the very close neutral *PET* values between the present study (27.4 °C) and Lin and Matzarakis' research (27.2 °C), within the reference comfort range (26–30 °C), thermal acceptability in L2 is only 53.8% as opposed to 88% in the case of Lin and Matzarakis [13]. Acceptability in this case is taken as the "no change" category in temperature preference votes [7]. Even when considering acceptability as satisfaction (-1<TSV<+1), it is 82.1%, which is still lower than Lin and Matzarakis' (2008) results. This indicates that the respondents are less tolerant than what is estimated by the sub-tropical comfort range. Such an outcome could be linked to the investigated activity (i.e. studying), which requires more favourable conditions compared to outdoor recreational activities of the referenced study.
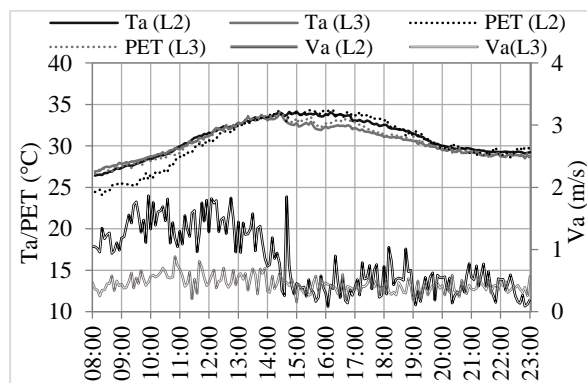
Figure 3. The physiological equivalent temperature, air temperature and air velocity variations in the studied spaces.
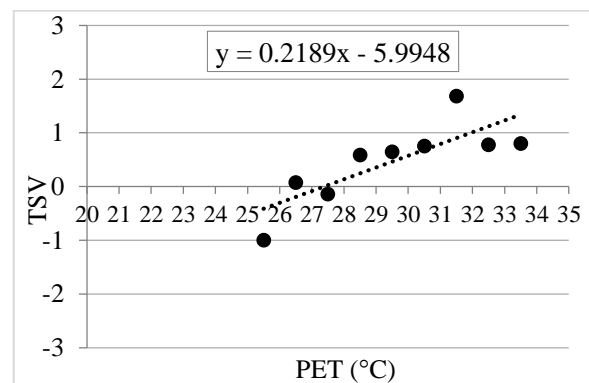
Figure 4. Thermal sensation votes and neutral *PET*.

3.3. *Personal factors*

3.3.1. Gender. An independent-samples t-test is conducted to compare thermal comfort votes between male and female participants. The result shows no significant difference in the scores for males and females (table 2). Gender does not have an effect on thermal comfort votes.

3.3.2. Ethnicity (Locals vs. Foreigners). Comparing thermal comfort votes between local and foreign respondents using t-test shows no statistically significant difference (table 2). Another test of thermal preference, however, shows a significant difference in the scores of locals (M=-0.54, SD=1.43) and foreigners (M=-1.73, SD=1.19); t (224)=2.71, p=0.007. This suggests that ethnicity has an effect on thermal preference, where foreigners prefer lower temperatures compared to locals. The findings are in line with attendance numbers in the adjacent spaces L1 and L2. During the two day investigation in L2 (warm semi-outdoor), it has been used by 9 foreigners and 83 locals. On the other hand, L1 (cold indoor) has been used by 39 foreigners and 76 local students during one day.

3.3.3. Cooling method preference. In response to cooling method preference, 13.7% of semi-outdoor respondents has chosen natural ventilation, 62.4% natural ventilation with fans and 23.9% air-conditioner. A one-way ANOVA is carried to evaluate the differences in thermal comfort votes based on participants' cooling method preference. The results illustrate a significant difference between groups; $F_{(2,223)}=6.636$, $p=0.002$. A Tukey post-hoc test has revealed that thermal comfort votes are higher for participants who prefer natural ventilation (M=0.48, SD=1.31, p=0.004) and natural ventilation with fans (M=0.21, SD=1.26, p=0.006) compared to those who prefer air-conditioner (M=-0.43, SD=1.22). There is no statistically significant difference between those who prefer natural ventilation and those preferring natural ventilation with fans (p=0.507). These results point to the changes in people's preferences and thermal comfort requirements, where they are becoming less tolerant to natural conditions due to their habituation to the air-conditioner.

3.3.4. Home temperature. A correlation of the data reveals that the perceived home temperature and thermal comfort votes are not significantly related (table 1). However, a significant correlation is found between the perceived home temperature and temperature preference, r=0.17, N=226, p=0.01. High temperature at home is associated with high preferred temperature.

3.3.5. Temperature in the previous space. Using t-test, this study has found that temperature of the previous space does not have an impact on thermal comfort votes. Comfort votes of participants "who were in a hotter space" does not differ significantly from those "who were in a colder space" (table 2). The adjustment time (15 minutes) given to the participants before answering the questionnaire could explain this result.

3.3.6. Expectations. A significant correlation between thermal expectations and thermal comfort votes is found (table 1). The closer the actual thermal conditions to respondents' expectations are, the higher the thermal comfort votes.

3.3.7. Time of exposure. In response to the question about the time to be spent studying in the two semi-outdoor spaces, the answers have varied between 0.5 hour and 12 hours, with an average of 2 hours and 18 minutes. However, no significant correlation is found between thermal comfort votes and the time to be spent in the area (table 1).

3.3.8. Perceived control. Using t-test, the comparison of thermal comfort votes between students working in a group and those working individually shows a significant difference (table 2). Students working in a group, where leaving the space in case of discomfort is partially controlled by the group, have lower thermal comfort votes compared to those studying individually—they have control over the decision to leave the space. This suggests that having control leads to better comfort.

3.3.9. Naturalness and environmental stimulation. Among the multiple reasons for choosing the studying areas (temperature, light, quiet, etc.), environmental beauty has been chosen by 22.6% of the respondents in the semi-outdoors spaces. A t-test shows a significant difference in the scores of thermal comfort votes between the respondents who consider the beauty of the environment as an influencing element in their space choice and those who don't (table 2). Participants who have chosen this element feel more thermally comfortable.

3.3.10. Behavioural adaptation actions. Among the different actions that could be taken to improve thermal comfort within the studying area, the respondents in the semi-outdoor spaces have chosen consuming cool drinks (64.2%), changing the area (52.7%), changing seating place (27.4%), extra piece of clothing (19.5%), USB fan (8.8%), hot drinks (3.5%) and other solutions (1.8%). In contrast, in the indoor space, the most prominent action has been wearing extra piece of clothing (66.1%), followed by

changing the area (33%), hot drinks (23.5%), changing seating place (20%), cool drinks (18.3%), USB fan (4.3%) and other solutions (1.7%).

Further analysis of respondents' actual clothing level (I_{cl}) in relation to PET shows that in the semi-outdoor spaces, I_{cl} does not correlate significantly with PET (r=-0.08, n=205, p=0.24). In contrast, in the indoor space, a significant correlation between PET and clothing worn by participants is found (r=-0.19, n=115, p=0.038). Low temperatures are associated with more clothing. In semi-outdoors' case, the insignificance may be linked to the fewer possibilities to change clothing due to the high temperature levels as participants already wear the minimum they can. In contrast, lower temperatures in the indoor space allow occupants to wear extra cloths or remove them in case of discomfort.

Table 1. Thermal comfort correlation with environmental and personal factors.

Pearson correlation		T_a	Temperature perception	RH	Humidity perception	V_a	Air velocity perception
Thermal comfort votes	r	0.05	-0.32	-0.31	0.05	0.38	0.31
	p	0.50	<0.01*	<0.01*	0.48	<0.01*	<0.01*
	N	226	226	226	225	205	226

Pearson correlation		T_{mrt}	Sun radiation perception	Home temperature perception	Expectations	Time of exposure
Thermal comfort votes	r	-0.02	-0.33	0.09	0.28	0.07
	p	0.75	<0.01*	0.19	<0.01*	0.31
	N	226	226	226	225	217

Table 2. Independent-samples t-test results.

T-test (Thermal comfort votes)		N	Mean	Standard deviation	t	df	p
Gender	Male	56	0.04	1.36	-0.382	224	0.703
	Female	170	0.11	1.27			
Ethnicity	Local	215	0.07	1.28	-1.193	224	0.234
	Foreigner	11	0.55	1.44			
Previous space is hotter	Yes	82	0.24	1.38	1.410	223	0.160
	No	143	-0.01	1.22			
Studying environment	Individually	70	0.46	1.47	2.756	219	0.006*
	Group	151	-0.5	1.18			
Naturalness	Yes	51	0.63	1.28	3.440	224	0.001*
	No	175	-0.06	1.26			

4. Conclusion

Based on the current findings, it could be concluded that thermal comfort is achievable in semi-outdoor spaces used for the long-term activity of studying. Furthermore, under suitable conditions, thermal comfort level in these spaces can even surpass an air-conditioned indoor. The suitable conditions include both objective and subjective factors. Besides air velocity being the most notable environmental factor

objectively affecting thermal comfort votes, this research has shown the subjective factors having the most significant impact. In this connection, occupants' perceptions of the different environmental conditions correlated better with comfort votes than the measurements did. Further, the different adaptation mechanisms are shown to be affecting thermal comfort votes' outcome or participants' thermal preference, including past experiences, expectations, perceived control and naturalness of the environment.

Acknowledgements

References

[1]   Chappells H and Shove E 2005 Debating the future of comfort: environmental sustainability, energy consumption and the indoor environment *Building Research & Information* **33** 32-40

[2]   O. Efeoma M, K. Ahadzie D, A. Ankrah N and Uduku O 2014 Assessing thermal comfort and energy efficiency in tropical African offices using the adaptive approach *Structural Survey* **32** 396-412

[3]   de Dear R and Brager G S 2001 The adaptive model of thermal comfort and energy conservation in the built environment *Int J Biometeorol* **45** 100-8

[4]   Wilhite H 2009 The conditioning of comfort *Building Research & Information* **37** 84-8

[5]   Cooper G 2008 Escaping the house: comfort and the California garden *Building Research & Information* **36** 373-80

[6]   Sinou M and Steemers K 2004 Urban semi-enclosed spaces as climate moderators. In: *The 21th Conference on Passive and Low Energy Architecture,* (Eindhoven, The Netherlands pp 1-5

[7]   Hwang R L and Lin T P 2007 Thermal comfort requirements for occupants of semi-outdoor and outdoor environments in hot-humid regions *Architectural Science Review* **50** 357-64

[8]   Ahmed K S 2003 Comfort in urban spaces: defining the boundaries of outdoor thermal comfort for the tropical urban environments *Energy and Buildings* **35** 103-10

[9]   Hani N, Nasir M, Salim F and Yaman M 2014 The potential of outdoor space utilization for learning interaction. In: *UMRAN2014,* (Kuala Lumpur: International Islamic University Malaysia) pp 1-17

[10]   Thorsson S, Lindberg F, Eliasson I and Holmer B 2007 Different methods for estimating the mean radiant temperature in an outdoor urban setting *Int J Climatol* **27** 1983-93

[11]   Givoni B and Noguchi M 2004 Outdoor comfort responses of japanese persons. In: *The 21th Conference on Passive and Low Energy Architecture,* (Eindhoven, The Netherlands pp 19-22

[12]   Metje N, Sterling M and Baker C J 2008 Pedestrian comfort using clothing values and body temperatures *Journal of Wind Engineering and Industrial Aerodynamics* **96** 412-35

[13]   Lin T P and Matzarakis A 2008 Tourism climate and thermal comfort in Sun Moon Lake, Taiwan *Int J Biometeorol* **52** 281-90