Post-occupancy evaluation of outdoor thermal comfort in hot arid zone

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Abstract

Human comfort and healthy environments lie at the core of every debate about outdoor spaces nowadays. Thermal comfort is a vital concern for planners and designers in order to produce a healthy and thermally comfortable environment, since the influence of different climates and user groups has been found to greatly alter the range of responses for thermal comfort calculations. This requires Post-Occupancy Evaluation (POE) with an integration of the appropriate outdoor thermal comfort (OTC) index. This paper presents the results of a detailed assessment for the OTC in hot arid zone (HAZ) using the most suitable thermal index. A case study was selected from Effat Campus, Jeddah, Saudi Arabia, to represent the HAZ. Subjective assessment employed the physiological equivalent temperature (PET) and the predictive mean vote (PMV) thermal indices in analysing the results of online and self-directed questionnaires while objective assessment employed a hand-held anemometer that was used to measure wind speed, whereas the wet bulb globe temperature (WBGT) SD Card Logger with a black globe thermometer 75 mm in diameter and emissivity of 0.95 was used to measure the globe temperature. The physical measurements were later used to calculate the mean radiant temperature (MRT) and consequently the PET index using RayMan Software. The results confirmed the significance of the shading strategy on OTC. The study revealed that there is no percentage as shading is permitting people to use the space; otherwise, in hot arid zone, the space would be completely unusable under the sun while the PET is more suitable than the PMV index.

Keywords: outdoor thermal comfort (OTC); OTC indices; MRT; PMV; PET

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1. INTRODUCTION

In a previous work [1], the authors systematically reviewed the suitable indices to assess the outdoor thermal comfort (OTC) in a hot arid zone (HAZ). After reviewing hundreds of research work, 59 research works [2–61] were reviewed thoroughly. The selection criteria were based on climatical zone (HAZ), the use of the OTC indices and the use of tools to measure the MRT. The results of the previous work revealed the following:

A. The PET is the most commonly used OTC index in the hot humid region,

B. The collected studies used the OTC index for one of different reasons as follows:
   1. Validation of the index
   2. Validation of a simulation software
   3. Difference between various urban areas, or urban morphology to generate design guidelines or measure influence of different mitigation techniques such as shade, vegetation and material
   4. Identification of the influence of one or each climatic variable on OTC
   5. Definition of neutral temperature, preferred temperature and acceptable range (calibrate the scale)
   6. View on the influence of culture on people's thermal perception
   7. The influence of an OTC on the usage of a public space

In contrast, most of the studies used the PET to indicate the influence of design on OTC or to adjust the scale as there is a need for adjusting proposed comfort/stress ranges of a given index when using it in different climatic contexts [28].

C. As for the tools or software used to calculate the OTC, there are a few tools that can assess either the OTC or mean radiant temperature in this field. However, the most common and comprehensive tools that can assess both OTC and the mean radiant temperature are RayMan and ENVI-met.
D. To measure the mean radiant temperature on site, the most common method is the use of a globe thermometer to measure the mean radiant temperature through the use of the previously mention Equation (2).

This paper investigates the OTC at a selected case study from Effat Campus, Jeddah, Saudi Arabia. Based on the previous results and recommendation, the PET, RayMan Software and the global thermometer will be employed to assess the OTC and the mean radiant temperature (MRT).

2. RESEARCH AIM AND OBJECTIVES

This research aims to study the influence of the shading strategy on OTC in the hot arid region. This aim could be fulfilled through the following objectives:

- Analysing the macroclimate of the city of Jeddah
- Following a specific detailed methodology to assess the OTC
- Investigating the OTC under the shade and outside the shade

3. RESEARCH METHODOLOGY

Online questionnaire, field monitoring and field surveys are used as data collection tools to select and assess the open space. The methodology follows a systematic procedure consisting of two main phases (Figure 1). The first phase is the subjective assessment for the users of Effat University. It is considered a preliminary data collection using an online questionnaire in order to gather data describing the user’s current usage of the outdoor space and its relation to OTC. The tactic used in this phase is a self-completion online questionnaire to obtain the essential data from the university users at a limited cost and a timely manner. The main objectives of the questionnaire are to establish the need for shade, to identify the open space that needs shade the most and to form an idea about the users’ shading preferences. The second phase is the subjective and objective assessment of the chosen open space. Two tactics are used, which are field monitoring technique and field survey. The field monitoring is done using filed equipment to assess the thermal comfort conditions objectively, while the field survey is used to assess the user’s thermal comfort subjectively. Both phases are dedicated to study the current condition and identifying the problem.

4. LOCATION AND CLIMATE OF THE CASE STUDY

The case study is conducted in the city of Jeddah in Saudi Arabia. It is considered one of the major urban centres in western Saudi Arabia. It is located along the red seacoast where it is a hot and humid climate. Real hour data have been recorded using a HOBO U30-NRC (Weather Station Starter Kit) which installed at Effat Campus. Figure 2 shows the weather station on top of the library building at Effat University. These weather data include air temperature, relative humidity, solar radiation, wind speed and direction, air pressure and rainfall level [62].
On obtaining the hourly climatic data, Weather Tool software is used to visualize and analyse the data. Jeddah features an arid climate under Koppen's climate classification. Unlike other Saudi Arabian cities, Jeddah retains its warm temperature in winter, which can range from 15°C at midnight to 25°C in the afternoon. Summer temperatures are very hot, often breaking the 40°C mark in the afternoon and dropping to 30°C in the evening. Rainfall in Jeddah is generally sparse and usually occurs in small amounts in December. There have also been several notable incidents of hail. Heavy thunderstorms are common in winter. Intense heating and humidity cause afternoon clouds almost every day. Daily highs are about 32°C while night-time temperatures average 22°C. Using Weather Tool and Mahoney tables, the recommended passive strategies and measures have been set out. The climatic analysis using Weather Tool, and Olgay Chart, confirmed that natural ventilation can enhance significantly the thermal performance of the building during the summer season in Jeddah (Figure 3).

Figure 4 shows the characteristics of the prevailing wind in Jeddah in terms of speed, direction and air temperature. It is obvious that the maximum frequency of prevailing wind occurs from the North and North West direction with an average speed of 20 Km/h, average wind temperature of 25–30°C and average relative humidity of 55–65%. The real recorded hourly weather data for Jeddah confirmed the outcomes of the synthesized data; however, it revealed the exact direction for wind during the day. Figure 5 illustrates that prevailing wind is coming from the North East at the morning and from the North and North West afternoon. The average wind speed varies between 10 and 15 km/h at 9:00 am and 3:00 pm; surprisingly, maximum wind speed is happening during the noontime from 12:00 pm to 04:00 pm to reach 48 km/h.

The choice of the open space to be studied was based on familiarity with the space and the various functions and activities taking place, the size of the area and accessibility to the site. Therefore, Effat University was chosen as the place to conduct the field study. Effat University is a private institution of higher education for women in Saudi Arabia. The University is in the south of Jeddah at ‘Al-Nazlah Al Yamiyyah’. The map in Figure 6 shows the layout of the buildings at Effat campus and the various selected outdoor spaces.

5. PHASE 1: DATA COLLECTION ‘ONLINE QUESTIONNAIRE’

The main purpose of the online questionnaire is to investigate the need for shade in Effat’s outdoor spaces and to identify the outdoor area that needs shade the most. The criteria for selecting the outdoor space depend on the level of usage, duration of usage and time of usage. Moreover, the questionnaire helps in recognizing the user’s shading preference in regard to the style and type of shade. The questionnaire is made up of closed-ended questions such as multiple-choice questions, rating scale questions, dichotomous questions and rank-order questions to yield a preliminary analysis of the current condition. The questionnaire is divided into three sections; each section is dedicated to achieving one objective. The first section is called the need for shade. It contains question about the usage of the outdoor spaces in relation to different variables of OTC. It also indicates the significance and the need for outdoor shade. The second section is an evaluation of the outdoor spaces on campus where the users are asked to determine their time or usage and duration of usage for seven outdoor spaces on campus. This will help in choosing the outdoor space that needs shade the most. The third section is devoted to form an idea about the users’ shading preferences where the users are asked questions about their preferences in regard to type of shading, style of shading, preferred material for shading and preferred type of structure. The questionnaire ends with an open-ended question asking the users to mention any comment or suggestion they have for the design of the shading elements.

As for the survey sample, it follows the non-probabilistic voluntary sampling method. There are several common survey errors such as under coverage, nonresponsive and measurement errors that must be dealt with to ensure that the survey will yield accurate results. The undercoverage error was handled by sending the questionnaire to the whole targeted population via the university’s email system, whereas the nonresponsive error was handled through a clear statement of the importance of participation and how the study might be beneficial to the participants as well.
as offering a two-value point for participating students as an incentive. As for the measurement error or vulnerable response bias, a pilot study was conducted to address poor question wording, wrong assumption behind the questions or wrongly focused questions.

5.1. Online questionnaire findings and discussion
The survey received a total of 419 responses from students, faculty and staff. The total number of students enrolled at the university is 1594, and the total number of participating students is 409 which means that 25.7% of the entire students participated in the survey.

5.1.1. Demographic profile
Of the respondents, 83.1% were between the age of 18 and 24. Ninety-nine percent of the respondents were female, while 97.6% of the respondents were students.

5.1.2. The significance of outdoor thermal comfort on the usage of the outdoor space
The first section of the survey revealed that 57.8% of the respondents use the outdoor spaces depending on the weather conditions; 64.2% of the participants confirmed that the thermal environment influenced their usage of the outdoor spaces on campus significantly. They clarified how the OTC influenced their usage of the outdoor spaces. Their responses can be categorized into the following points:

- They avoid going any place where they might be exposed to intense solar radiation even if they want to go.
- They look for shaded areas to go to classes even if it takes more time.
- They use shortcuts to avoid the hot weather or they use the bridges between buildings to get to classes.
- When the weather is comfortable, they spend more time outdoors, and when the weather is hot or humid, they go inside or limit their time spent outdoors.

This shows that there is a great need to enhance the OTC in order to encourage the use of the outdoor spaces. This point is further proved when the respondents were asked to rank the reasons that encourage them to use the outdoor spaces in campus; their responses in order of importance were as follows:

- Comfortable thermal environment (suitable weather conditions, availability of shade)
Aesthetic design  
• Held events  
• Available services (café, restaurants)  
• Distance

Two-hundred thirty-seven respondents chose comfortable thermal environment as the first factor that encourages them to use the outdoor spaces on campus, where 93.6% of the respondent confirmed their willingness to spend more time outdoor if the thermal performance enhanced. This shows that there is a high possibility of using the outdoor spaces more if a climatic design approach was to be considered.

5.1.3. The need for shade
The first section of the survey proves the need for shade where 93.1% of the respondents noted that they look for shade when using the outdoor spaces on campus, and 85.7% of the respondents believe that there are not enough shaded areas on campus. Moreover, when respondents were asked what type of action they prefer to take when the weather is too hot outdoors on campus, even though 48.9% choose to leave, 40.6% choose the option of moving to a shaded space. All these prove the need for shade and the possibility of using the outdoor spaces more once efficient shading is provided.

5.1.4. Selection of the outdoor space that will be studied
The second section of the questionnaire was titled ‘Evaluation of the outdoor spaces on campus’. It was dedicated to select the outdoor space that needs shade the most based on time and duration of usage.

The outdoor space that needs shade the most is outdoor space Number 6 ‘Paul café area’ (refer to Figure 6) where it ranked the highest in both time of usage and duration of usage, where more than 50% of the respondents use it from 20 min to 2 h every day or even more. Therefore, Outdoor 6 was selected as the study site to be assessed.

Figure 4. Wind frequency, average wind temperature, average relative humidity and average rainfall, after Weather Tool.

Figure 5. Wind direction and speed in Jeddah, after Weather Tool.
5.1.5. The users’ shading preferences

The third and final section of the questionnaire gives an idea about the campus users’ preferences regarding different aspects of the shading design. From the users’ responses, the first preferred type of shading is natural shade while they prefer the shade to be movable to allow air movement in the absence of solar radiation. As for the style of shading, 44.6% prefer the shading style to be in harmony with the surroundings. The preferred type of material is between flexible material and semi-rigid material, and the preferred shading structure is the tensile structure.

6. PHASE 2: ASSESSMENT OF OUTDOOR THERMAL COMFORT AT THE SELECTED OPEN SPACE ‘PAUL CAFÉ AREA’ ‘SURVEY AND FIELD MEASUREMENTS’

The second phase is the Post-Occupancy Evaluation (POE) that included subjective and objective assessments for the thermal condition of the selected open space. A field survey was conducted with the users of the space to obtain data about their thermal perception. The field survey included closed-ended questions to form statistical analysis regarding the user’s thermal perception. The questions of the field survey included eight questions about the personal information, clothing, activity and 7-point American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) scale for human thermal comfort. The survey receives a total of 51 responses. Forty-one of the responses were from students, and 10 were from faculty and staff. Eighty-nine percent of the respondents wear ‘Abaya’ (black long garment that absorbs heat). This clothing type lowers thermal comfort, rather than the typical white garment of males at Saudi Arabia. The results also confirmed that the activities in this place are varied from sitting to standing and walking. The survey results were used to calculate the average users’ thermal perception on the 7-point scale and compare it to the PET values of the physical measurements. The responses varied between slightly warm, warm and hot. Only 1 respondent reported cool, 2 reported slightly cool, 17 as neutral, 16 feels slightly warm, 8 feels warm and 7 feels hot.
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Table 1. Human thermal comfort based on the survey results.

| Thermal sensation | Survey responses | Rate | Total |
|--------------------|------------------|------|-------|
| Cold               | 0                | -3   | 0     |
| Cool               | 1                | -2   | -2    |
| Slightly cool      | 2                | -1   | -2    |
| Neutral            | 17               | 0    | 0     |
| Slightly warm      | 16               | 1    | 16    |
| Warm               | 8                | 2    | 16    |
| Hot                | 7                | 3    | 21    |

Average thermal sensation 0.98

Simultaneously, measurements of the environmental parameters (air temperature, relative humidity, wind speed and MRT) were carried out at the pedestrian level 1.5 m except for wind speed that was measured at a point far away from any obstruction (2.2-m height). The measurements were taken at two points: under the direct sun and under the shade of the selected site ‘Paul café area’ to compare between the thermal performance objectively. The measurements were taken from 9:30 am to 4 pm on 11 April 2019. The measurements were taken for 1 day due to time limitation. The following tools were used to conduct physical measurements of the environmental parameters to obtain climatic data about the selected site. The Hobo-12 data logger shown in Figure 7a was used to measure the air temperature and relative humidity. A handheld anemometer shown in Figure 7b was used to measure wind speed. Whereas the WBGST SD Card Logger with a black globe thermometer 75 mm in diameter and emissivity of 0.95 shown in Figure 7c was used to measure the globe temperature. The physical measurements were later used to calculate the

Table 1 summarizes the results of the thermal sensations of the respondents to the 7-point ASHRAE scale. The table shows that the average thermal sensation on ASHRAE scale is 0.98. Using square-one predicted mean vote (PMV) calculation revealed a 25.5% dissatisfaction percentage (PPD).
MRT and consequently the PET index.

Figures 8 and 9 show the monitored measurements in both the shaded and sunny areas. Measurements show high air temperatures for most of the time where it ranged between 30.7 and 25.18°C with an average of 33.5°C under shade, while it ranged between 29.5 and 43.6°C with an average of 39.9°C. Relative humidity ranged between 45.9 and 56.6% with an average of 49.4% under shade, while it ranged between 31.5 and 46.3% with an average of 36.5%, considering that the comfortable range of relative humidity (RH) for human beings ranges from 40 to 70% [63] confirmed the suitability of the RH in the shaded area. Illuminance ranged from 3606.8 to 29 189.6 lx with an average of 6872.7 lx under shade while it ranged from 4533.3 to 34 280.1 lx with an average of 31 486.3 lx. Air velocity ranged between 0.1 and 2.1 m/s with an average of 1.5 m/s under shade while it ranged from 0.05 to 1.9 m/s with an average of 0.8 m/s in the sunny area.

After acquiring the necessary measurements and calculating the MRT using the recorded globe temperature, wind speed and air temperature in the previously mentioned Equation [2], a model of the studied site was created using the RayMan Software. Figure 10 shows the modelled version of the site using the RayMan software. The model shows the surrounding environment of the selected site that includes the architecture and the humanities building on the north, the business and engineering building on the south and a bridge from the north to the south that connects all the four buildings. The model also includes a kiosk, Paul café and its shaded sitting area as well as a number of scattered palm trees through of the site that all can be seen in Figure 11 that also shows the two points of measurements Point 1 under shade and Point 2 under the sun.

In order to compare between the sunny and shaded areas objectively, the PET index (Table 2) was calculated using the RayMan software. The program requires several input variables in order to perform the necessary calculations. First, the geographic location and time zone were set to match the chosen site. Second, the recorded microclimate measurements and the mock-up digital model of the studied area were used as input data. Third, the personal data regarding the height, weight, age and gender were set to fit the description of the average student as they make up most of the population on campus, whereas the clothing and activity rate are always set as at 0.9 clo and 80 w for the calculation of the PET, respectively. The PET index was calculated for each hour of the day from 9 am to 4 pm for both the shaded and sunny area as
seen in Figure 12. The PET values for the sunny area ranges from 38.7 to 48.9 whereas the PET values for the shaded area ranges from 32 to 34.6. The PET values of the sunny area indicate that the thermal perception at the beginning of day is considered 'hot' but quickly changes to 'very hot' where people experience an extreme level of heat stress. As for the shaded area, the PET value shows that thermal perception is 'warm' throughout the whole day where people experience moderate heat stress. This proves the extreme significance of shading where it reduces the high risk of extreme heat stress, while respondents confirmed that staying out in the sun is not even a viable option due to the negative thermal environment.

According the survey results, the overall subjective assessment reveals that the average thermal perception of the respondents under shade is equal to 0.98 which means that the respondents feel 'slightly warm'. However, the average PET for the whole day indicates that the thermal environment is perceived as 'warm' which is one level higher on the thermal perception scale. This difference between the overall subjective and objective assessment is possibly due to different adaptation methods that include behavioural adaptation such as consuming a cold drink or psychological adaptation where people's past experiences greatly influence their expectations of the existing thermal environment. Another adaptation method is physiological adaptation such as acclimatization where people become gradually accustomed to warmer conditions after ample exposure. This further proves that people within different climatic regions have a different comfort range. A study in Cairo, Egypt, which is similar to the climate of Jeddah revealed that the neutral range for the PET in the city of Cairo is between 21.6 and 30.1°C [64]. Therefore, when comparing the average PET values for the whole day that is 33.7 to the neutral comfort range in Egypt, it indicates that the calculated PET value is considered 'slightly warm'. Hence, the objective and subjective assessment results match proving that the PET index is a suitable index for OTC in Jeddah once the scale is adjusted to represent the true comfort range of this particular climate.

Taking a closer look at the hourly PET values and the corresponding thermal perception of the users, it was found that during the last hour of the day between 3 and 4 pm, people started to feel slightly cooler, and the PET value was at its second lowest at 32.6°C as the cross ventilation increased. The reason behind the improvement of cross ventilation is the increase in difference between the air temperature in the sun and under the shade triggering the phenomenon of deferential pressure that in return increases the air movement. The increase in wind velocity allows the air to circulate and encourages the human body to sweat and get rid of the excessive latent heat. This is considered one of the advantages of the shading strategy not only to block solar radiation, but more importantly, it helps create differential pressure between the sunny and shaded area enabling an increase in wind velocity. This is proven as a highly effective way to deal with high humidity and achieve a better thermal environment.

Additionally, the data obtained from the field study was used to calculate the PMV index. The calculated average PMV value under shade based on physical measurements that was 2.59 shows a great discrepancy from the subjective assessment. This implies that the PMV is not a suitable index to measure the OTC.

This study was intended to determine the percentage of enhancement that shade provides in terms of thermal comfortability against the areas exposed to the sun. However, the study revealed that there is no percentage as shading is permitting people to use the space that otherwise would be completely unusable under the sun. Therefore, this indicates that shading is not an option; it is a must for the outdoor spaces to be functional in the hot arid zone.

7. CONCLUSION

This paper was mainly concerned with investigating the OTC subjectively and objectively using field measuring equipment and a survey. These results revealed the following:

- The influence of shading on OTC and how significant it is in the success of the open spaces where the availability of shade makes an open space functional as opposed to an open space exposed to the direct sun where it is rarely used due to the negative thermal environment.
- The thermal sensation of occupants has been enhanced significantly after 3:00 pm when the air speed increased to around 1.7 m/s indicating the importance of cross ventilation in shade design as well as its positive influence on the thermal environment in the hot humid region.
- Relative humidity lies in the comfort zone of human being under the shade 'with an average of 49.4' whereas it is below the comfortable zone in the sunny are 'with an average of 36.5'.
- The PET values for the sunny area ranges from 38.7 to 48.9 'very hot' whereas the PET values for the shaded area range from 32 to 34.6 'warm'. This proves the extreme significance of shading where it reduces the high risk of extreme heat stress.
- The PET was proven as a suitable index for measuring the PET in Jeddah with the slight difference to people's thermal perception due to possible adaptation measures. However, if the scale is adjusted to suit the climatic conditions of the city of Jeddah, more accurate results will be formed.
- The PMV was proven to be an unsuitable index for measuring the OTC as there was a great level of inconsistency between the calculated PMV values and the user's thermal perception.

Since people felt warm during the time of field study on early April 'spring season', people are expected to feel very hot in the summer season. This emphasizes the urgent need for appropriate shading strategies with enough consideration for air movement and average level of humidity to achieve a better thermal environment that in return contributes to the success of the open space.
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