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RESEARCH ARTICLE

The Influence of Outdoor Space Geometry and Greenery Configuration on Students' Thermal Perception during Moderate Seasons in an Arid Climate

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Abstract

Improving the outdoor thermal sensation helps improving the quality of outdoor spaces for pedestrians and users, consequently contributes to making cities more sustainable. Space geometry and space greenery are acknowledged for their impact on outdoor thermal comfort. However, limited studies examine both strategies simultaneously. This study aims to determine experimentally the degree by which space geometry, materials, and greenery affect outdoor thermal comfort for space users. Two spaces at university campus at El-Giza, Egypt were selected as a case study. Space 1 had a favorable geometric configuration as it had 75% of its perimeter enclosed by 6 floors building and oriented towards the prevailing wind, however, it was completely paved. Space 2 had more than 60% of its surface covered by greenery with 50% of its perimeter enclosed by the same building and its western and southern sides were opened. The relevant climatic parameters were measured and surveys were distributed among 290 students over six days in spring and four days in fall during typical educational day hours in the two spaces. Throughout all measurements taken, Space 1 enjoyed cooler air temperature, Mean Radiant Temperature (MRT) and Physiological Equivalent Temperature (PET). Students with "Neutral" thermal conditions in Space 1 were twice the number of their peers in Space 2 and the number students who generally perceived Space 1 as thermally "comfortable" was higher than in Space 2. The results objectively (PET) and subjectively (self-reported survey) imply that space geometry manipulation had stronger effect on students' thermal sensation than space greenery.

Keywords: Outdoor Thermal Comfort; Physiological Equivalent Temperature (PET); Thermal Sensation Vote (TSV); University Campuses

Introduction and Background

Studies on outdoor thermal comfort are essential for comprehending how people react to their thermal surroundings. This knowledge can serve as a foundation for forecasting how urban outdoor space users will behave under different thermal conditions. It has become evident that creating comfortable outdoor urban spaces can enhance the quality of life. Given that over half of the world's population lives in cities, outdoor recreational areas have a substantial impact on people's physical, social, and mental health [1-3]. The improvement of the thermal conditions of outdoor spaces can result in energy savings in buildings as people will spend more time outdoors. Furthermore, the access restrictions have complicated the role that parks and outdoor areas play in promoting psychological and physiological recovery during the pandemic crisis [4,5].

Outdoor thermal comfort is one of the most important indicators that affects the usability of outdoor urban spaces from the perspective of the residents of urban environments [6]. Some climatic variables, like air temperature, wind speed, relative humidity, and mean radiant temperature can significantly affect outdoor thermal comfort. By understanding regional climatic changes and thermal comfort indicators at the micro-scale, improving the quality of outdoor spaces with all its economic benefits becomes possible. On the other hand, outdoor thermal comfort is not solely affected by environmental variables; there are additional parameters, that have a major impact on the thermal sensation of the space users such as activity level and clothing [7,8]. The characteristics of the built environment (space geometry, materials, and vegetation) affect thermal comfort.

Literature Review

In previous studies, personal factors such as age, gender, and body weight were reported to have a significant effect on human thermal comfort [9-11]. Many studies comprehensively choose the individuals formulating their samples without controlling for age variations [12-15]. In the study at hand, through an experimental approach, we aim to explore the extent to which the built environment can affect the thermal sensation of outdoor space users. Outdoor thermal comfort was investigated in many previous studies with different climate classifications. Lin [10], Mahmoud [11], Sangkertadi [12]. Many of the outdoor thermal comfort oriented studies in the MENA region examine the outdoor thermal comfort through simulation studies such as in [19]. Fewer studies mix simulations with field measurements [20,21] or studies that solely depend on field measurements [12,22]. However, studies that examine simultaneously the impact of vegetation and space geometry on outdoor thermal comfort and compare their impact are more limited.

The study at hand discuss the influence of building form and outdoor greenery on outdoor thermal comfort and which of the two variables have the strongest effect on overall thermal comfort. This is achieved through answering the following inquiry: Among space geometry manipulation and outdoor space greenery, which strategy is more effective in improving outdoor thermal conditions in arid climates? The sample of individuals used within this study is formed from university students who are within the same age range. The study was spatially performed within two university outdoor spaces that are significantly different in terms of their geometric configuration, orientation, and materials. The climatic measurements were simultaneously taken in the two spaces. Hence, it was possible to attribute any change in the thermal sensation of users solely to variations in the built environment. The findings of this study cast light on the impact of micro-scaled variations in the built environment and how they influence the thermal perception of users in the outdoors.

Data and Methods

The analysis was methodologically divided (as shown in figure 1) into the following primary categories; a) self-reported results that adhere to ASHRAE 55 and ISO standards, b) field climatic measurements.

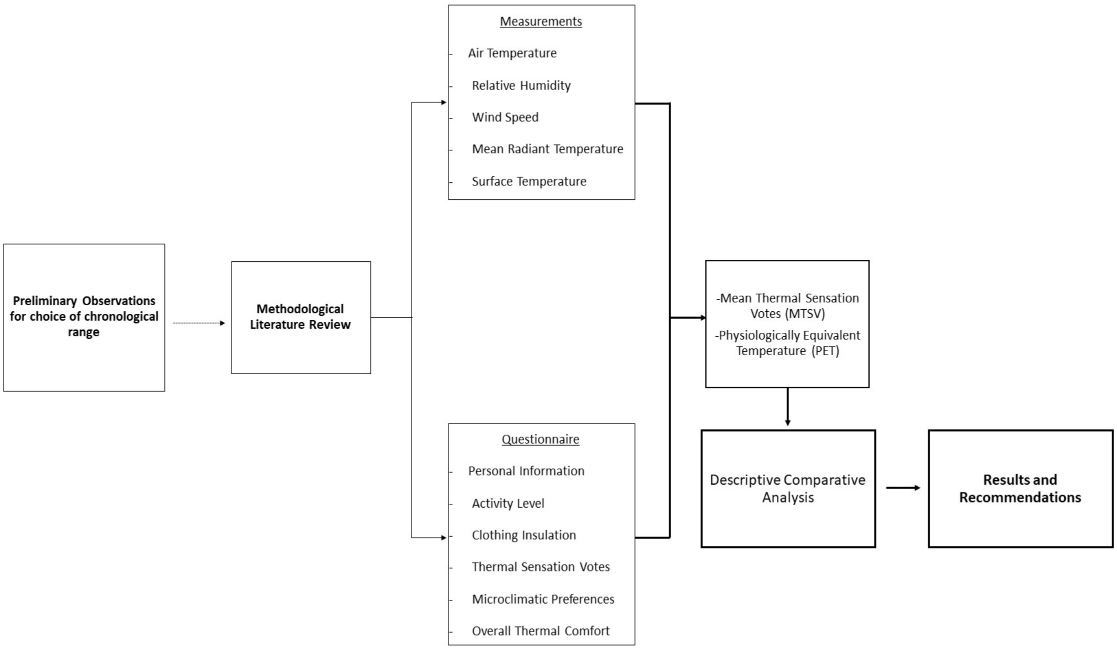


Figure 1: Workflow demonstrating the methodological steps conducted in the study.

Study Domain

The study was carried out at Smart Village in Giza, Egypt. According to Köppen's classification of climates [23], Smart Village has a BWh which is a dry and hot desert climate. As a result, there is only an average of 4mm of rainfall per year, mostly in the winter month of January. The minimum average temperature of 12.5°C throughout the winter which is considered warm. Even though the summer is hot and dry, August is the hottest month and has an average temperature of 28.3°C. May is regarded as the driest month of the year because it has 0mm of rainfall [24]. Therefore, may have the lowest relative humidity, at 37.68 percent, while December has the greatest relative humidity of 56.59 percent. Our study compared the climatic variables that were measured in two spaces and the usability of the users according to their different gender. The study was conducted in a university campus in Smart Village which is situated at (30.072°N, 31.018°E) and 75 meters above sea level [25]. Giza, Egypt has a dry and hot desert climate Köppen's classification of climates BWh [26].

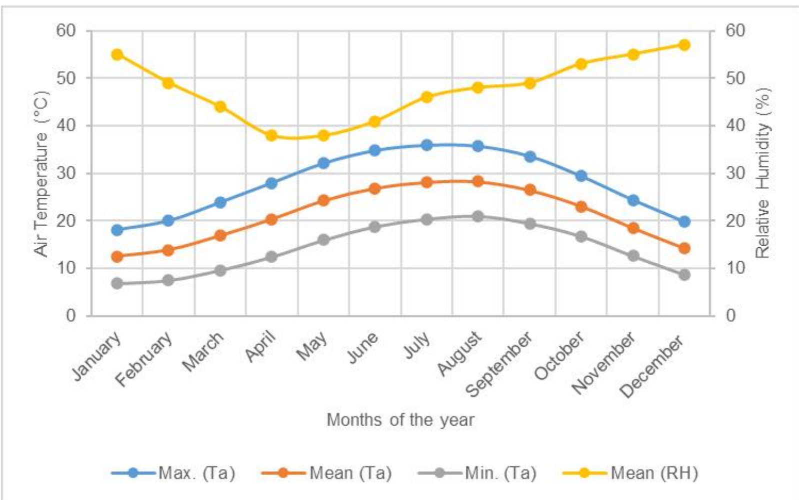


Figure 2: Monthly mean, the maximum, minimum air temperature on the 6th of October, Giza, Egypt (by the author according to data from [24].

The study was conducted within a university campus but in two different spaces (figure 3) throughout the same day. The first space (Space 1) is the primary outdoor public area which is oriented to the north west and facing the direction of the prevailing wind in an unobstructed manner with roughly 1148 m² in size and was surrounded by glazed high buildings which partially shaded some parts of the space for long periods of the day. The surrounding building's finishing materials are mainly glazing. The flooring finish is made of granite and interlocking marble tiles. The second space (Space 2) is not as exposed to the prevailing winds and orientated to the south with a 1333 m² and was mainly designed as to be the entertainment space for the students with two garden areas of which a small area (approximately 150 m²) is shaded by wooden pergolas and surrounded by palm trees. Except for minor portions that are partially shaded by nearby buildings and areas covered by the pergolas, the majority of Space 2 is exposed to solar radiation. 60% of the area of Space 2 is covered by greenery. The paved parts of the space are floored with interlocking concrete tiles. The remaining areas have grass as ground cover with palm trees. The building façade is finished with the same materials as in space 1.

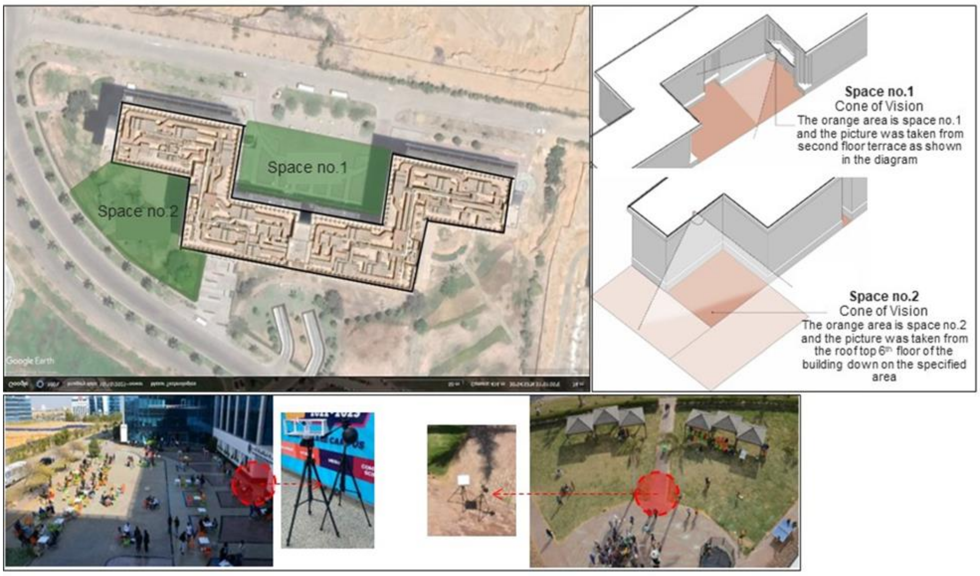


Figure 3: a) The top left photo is a satellite image for AASTMT university buildings with the two selected spaces. (Map data: Google Earth, Image @ 2022 Maxar Technologies). b) The top right is a mass model to indicate the locations from the vintage points that the pictures were taken from. c) The below left photo is space no.1 with the location of the measurement tools although the right below photo is space no.2 with the selected location of the measuring tools.

The Climatic Field Measurements

The field measurements were taken in spring and fall. Among the limitations of this study is that we were not able to conduct the analysis during summer and winter as the number of students was significantly lower. The measurements were carried out for ten days and covered the microclimatic parameters that affects outdoor thermal comfort based on ASHRAE Standard [7]. The measured parameters were air temperature (°C), wind speed (m/s), and relative humidity (%), in addition, to mean radiant temperature (MRT) (°C), and ground surface temperature (°C) which is according to many previous studies [12-15]. In this study, Physiological equivalent temperature (PET) was used as an indicator of outdoor thermal comfort. While newer thermal comfort indices were developed like Universal Thermal Climate Index (UTCI), PET was found to be highly correlated with UTCI under different climatic conditions [27-30]. For a human biometeorological examination within the urban climates, the PET validity has been provided in different climatic conditions such as hot/ arid and hot/humid conditions, and has already included in the German VDI3787 [31]. At last, but not least, PET can be calculated using the open-access software Rayman.

The survey responses for the pedestrians' subjective thermal perceptions were gathered while the measurement tools were in place. Two video cameras were placed throughout the day to determine the pattern of space use/ occupancy by the students in both spaces [32]. The study survey was conducted in March, May, and November in 2022 with six days of measurements in spring and four days of measurements in fall.

A portable Pasco wireless weather sensor with GPS (PS-3209) was used to collect data for microclimatic variables, as recommended by the American Society of Heating, Refrigerating and Air-Conditioning Engineers Standard (ASHRAE) [7]. A thermal camera (testo 865) was used to measure the surface temperature; Globe temperature (Tg) was taken with a 150mm diameter black matte globe thermometer connected to a Testo 440 device placed at a height of 1.1m. The following equation 1 was also used to calculate the mean radiant temperature (Tmrt) [33,34].

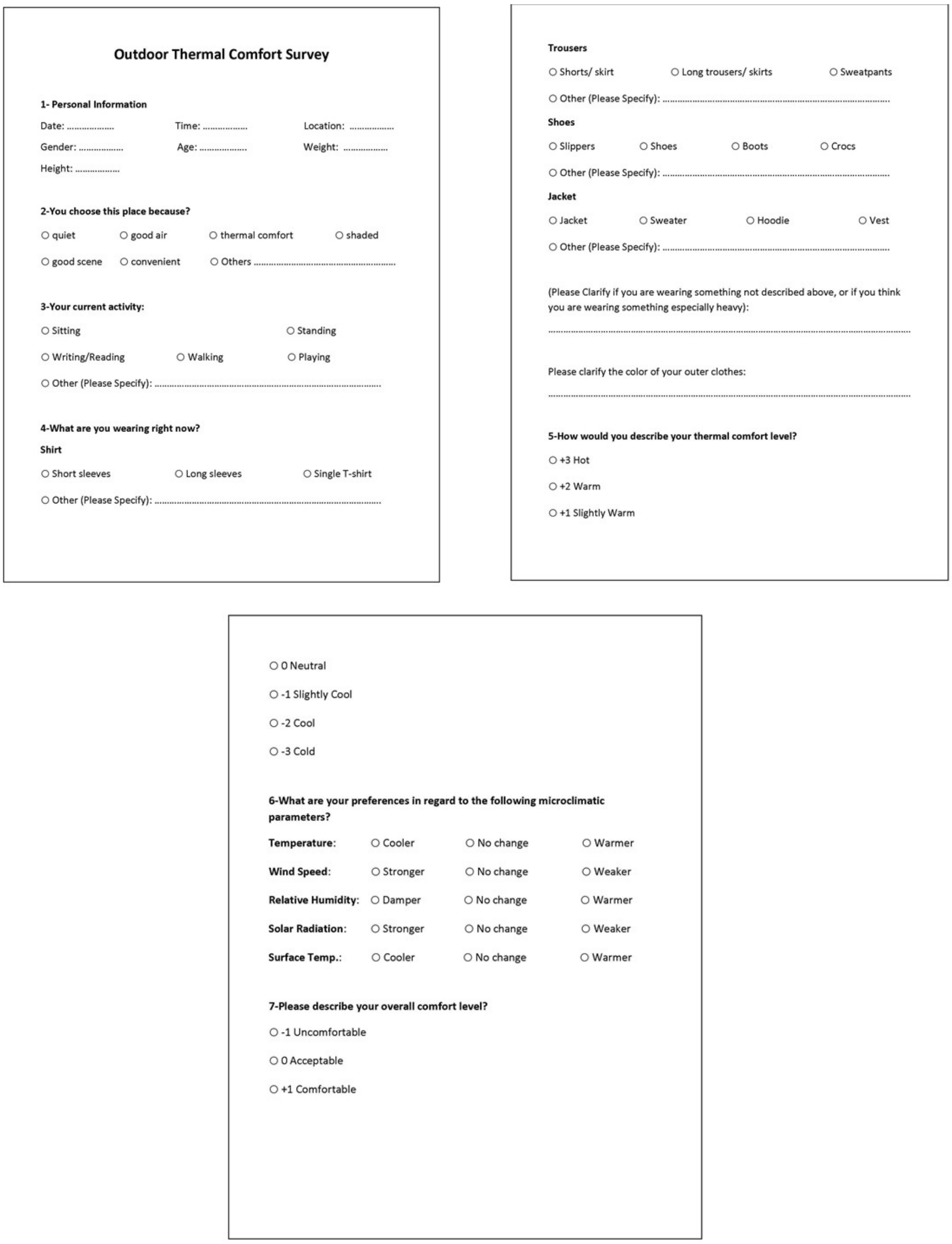
Where Tg is the globe temperature (°C), Va is the wind speed (m/s), Ta is the air temperature (°C), Ɛg is the globe's emissivity (0.95 for the black globe), and D for the globe diameter (150mm). The PET was then calculated by inputting the measured climatic parameters into the software Rayman model version 1.2 [35]. Rayman is a software that was developed in the Meteorological Institute, University of Freiburg, Germany, according to the German Engineering Society Guidelines (VDI, 1998). Rayman is regarded as one of the most rigorous models for bioclimate calculations. The model requires values of air temperature, wind speed, relative humidity and mean radiant temperature as inputs in addition to some personal data as (Height, weight, age, gender, clothing insulation, activity level) to calculate PET as an output.

Table 1: Equipment specifications and features.

Parameter monitored	Sensor Brand and Model	Tool's Picture	Accuracy	Response/ Adjustment Time	Resolution	Measurement Range
Air Temperature	Pasco Wireless Weather Sensor with GPS (PS-3209)		± 0.2 °C	5 min.	0.1 °C	- 40 to +125 °C
Relative Humidity	Pasco Wireless Weather Sensor with GPS (PS-3209)		± 2 %	5 min.	0.1 %	0 to 100 %
Wind Speed	Pasco Wireless Weather Sensor with GPS (PS-3209)		3 % of reading	5 min.	0.1 m/s	0.5 to 15 m/s (winds of up to ~ 33 mph)
Mean radiant temperature	Testo Globe Thermometer (D = 150mm)		At 22 °C ± 1 digit (type K thermocouple, class 1)	Approx. 30 min		0 to +120 °C
	Testo 440 device		(± 1 digit) ± 0.4 °C (-40 to -25.1 °C) ± 0.3 °C (-25 to +74.9 °C) ± 0.4 °C (+75 to +99.9 °C) ± 0.5 % of m.v. (remaining measuring range)	5 min.	0.1 °C	- 40 to 150 °C
Thermal camera	Testo 865		± 2 °C, ± 2 % of measurement value (larger value applies)			- 20 to +280 °C

The Survey

A self-reporting survey was conducted along with the objective microclimatic monitoring, and the represented sample was comprised mainly of students with approximately equal ratio between males and females. In this study all the surveyed students were all within the same age range, and their positions were not further than 30m from the measuring tools [36]. The questionnaire had mainly three parts following [33,37]. The personal information was requested in the first section of the thermal comfort questionnaire as shown below in Fig. 4, following [38, 39] such as (e.g., age, gender, activity, time spent in outdoor spaces, and motivation behind their choice to the outdoor space). The second section recorded, the clothing layers, along with the color of their clothing. Equivalent values for these data were then estimated Clo-units in addition to Metabolic rate (W/M2) based on the [8]. All the aforementioned values were used as inputs in Rayman to calculate PET for each survey. The third and final section dealt with the subjective measurements such as the participants existing thermal perception and preferences for all climatic parameters, with the ASHRAE 7-point thermal sensation vote (TSV) scale (−3, cold; −2, cool; −1, slightly cool; 0, neutral; 1, slightly warm; 2, warm; 3 hot). The McIntyre preference scale where each participant specifies if they want the climatic parameters to be (“cooler”, “no change”, or “warmer”) was used. Finally, the overall thermal comfort (uncomfortable/ acceptable/ uncomfortable) was also reported. The outputs of the survey were used as inputs for the calculation of the Mean Thermal Sensation Vote (MTSV) in addition to documenting the user’s personal characteristics. Two hundred and ninety participants were interviewed (of which 43% were females and 57% were males). The majority were between 18 and 23 years of age (85%) and 15% or the age between 23 to 30 years old. All the surveyed students used the outdoors of the university daily with a minimum duration of 20 min.



Outdoor Thermal Comfort Survey

1- Personal Information

Date: ……………… Time: ……………… Location: ………………

Gender: ……………… Age: ……………… Weight: ………………

Height: ………………

2-You choose this place because?

○ quiet ○ good air ○ thermal comfort ○ shaded

○ good scene ○ convenient ○ Others ……………………………………

3-Your current activity:

○ Sitting ○ Standing

○ Writing/Reading ○ Walking ○ Playing

○ Other (Please Specify): ……………………………………

4-What are you wearing right now?

Shirt

○ Short sleeves ○ Long sleeves ○ Single T-shirt

○ Other (Please Specify): ……………………………………

Trousers

○ Shorts/ skirt ○ Long trousers/ skirts ○ Sweatpants

○ Other (Please Specify): ……………………………………

Shoes

○ Slippers ○ Shoes ○ Boots ○ Crocs

○ Other (Please Specify): ……………………………………

Jacket

○ Jacket ○ Sweater ○ Hoodie ○ Vest

○ Other (Please Specify): ……………………………………

(Please Clarify if you are wearing something not described above, or if you think you are wearing something especially heavy):

……………………………………

Please clarify the color of your outer clothes:

……………………………………

5-How would you describe your thermal comfort level?

○ +3 Hot

○ +2 Warm

○ +1 Slightly Warm

○ 0 Neutral

○ -1 Slightly Cool

○ -2 Cool

○ -3 Cold

6-What are your preferences in regard to the following microclimatic parameters?

Temperature:	○ Cooler	○ No change	○ Warmer
Wind Speed:	○ Stronger	○ No change	○ Weaker
Relative Humidity:	○ Damper	○ No change	○ Warmer
Solar Radiation:	○ Stronger	○ No change	○ Weaker
Surface Temp.:	○ Cooler	○ No change	○ Warmer

7-Please describe your overall comfort level?

○ -1 Uncomfortable

○ 0 Acceptable

○ +1 Comfortable

Figure 4: The self-reporting survey for the thermal comfort questionnaire by the author and according to (“ASHRAE Standards 55,” 2004; *ISO 7730*, 2005).

Results and Discussion

The microclimatic variables were measured and analyzed for both spaces as shown below in figure 5. The measurements were taken during the daily break times and for six days in spring and four days in fall. The geometric variations between the two spaces have led to miscellaneous differences in the microclimatic conditions as per demonstrated by the measurements. Due to its orientations, space 1 has consistently enjoyed lower MRT, air temperature and average surface temperature values in comparison to space 2. This was reflected on the overall thermal sensation of the students. For example, during the hottest examined day, air temperature reached as high as 35 °C in space 2 while not exceeding 30°C in space 1. At the same timing the average PET values in space 1 were approximately 30 °C while exceeding 50 °C in space 2. Two additional points are worth noticing.

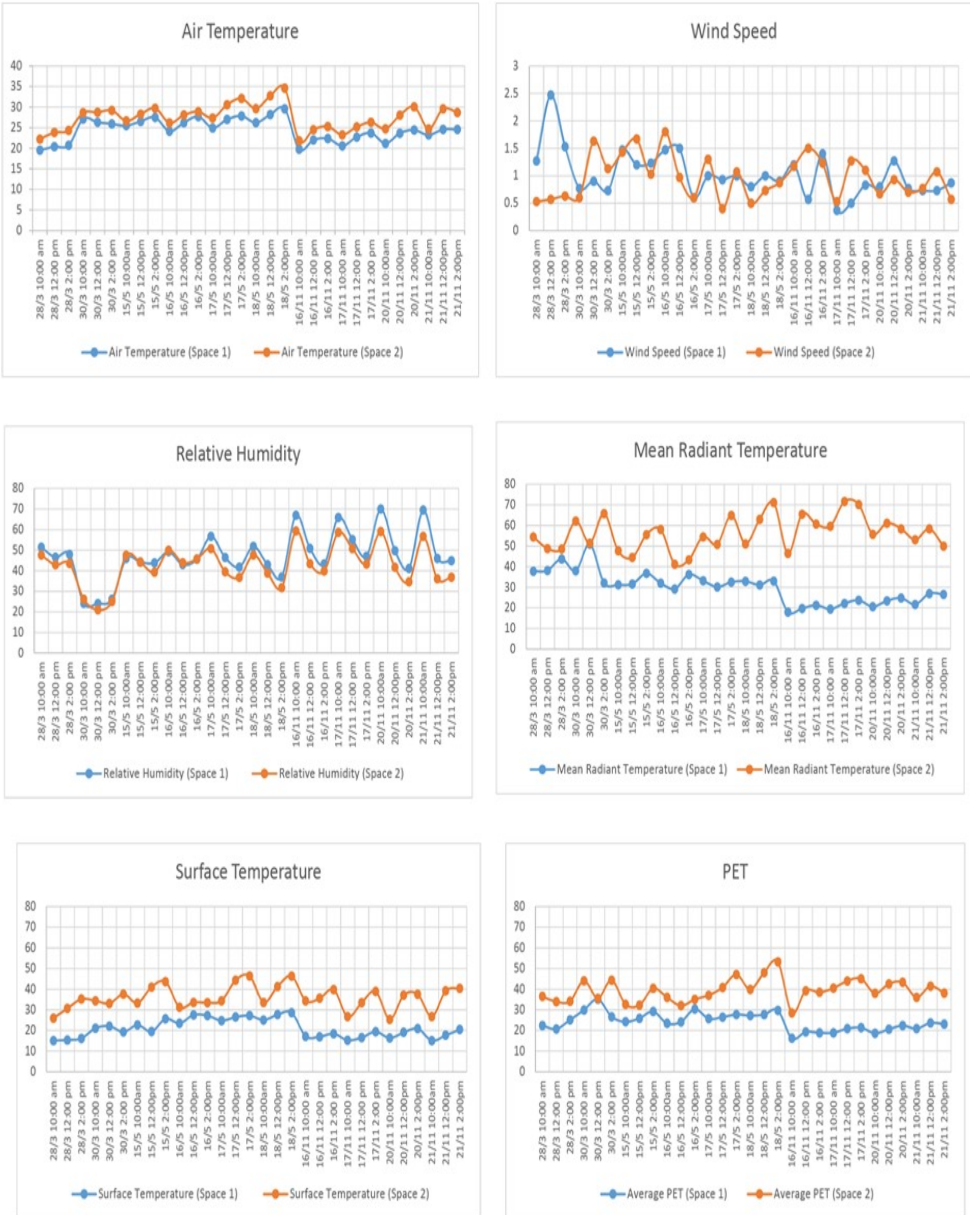


Figure 5: Comparison between the microclimatic conditions in the two spaces.

Firstly, it appears that the thermal performance of the two spaces is more sensitive to changes in space geometry during fall in comparison to spring. This can be noted as the differences between the calculated PET and MRT values are much higher in fall in comparison to spring. Secondly, despite not containing any vegetation or green ground cover, Space 1 enjoyed a consistently improved thermal environment in comparison to Space 2.

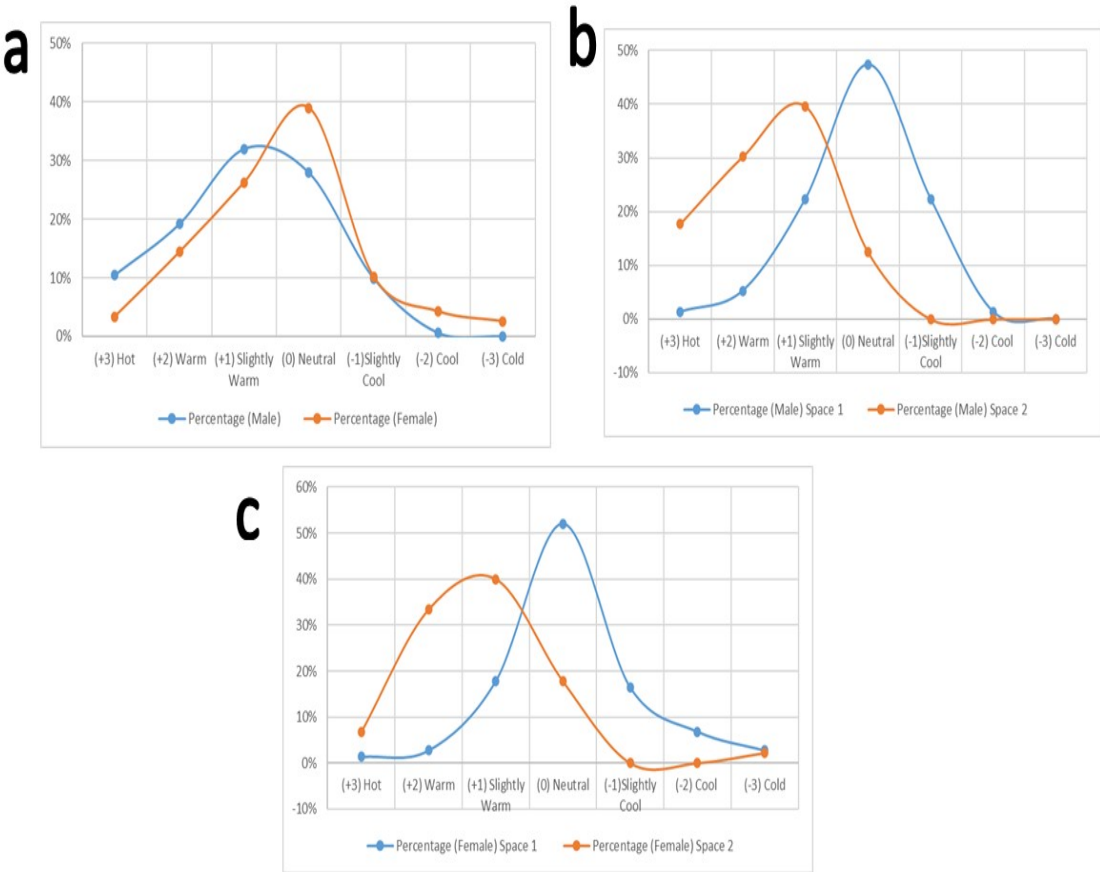


Figure 6: a) Thermal sensation votes (TSVs) percentages distribution in the two spaces for all the students, b) TSV percentage distribution for males in the two spaces, and c) TSV percentage distribution for females in the two spaces.

To further improve the understanding of the participants' thermal perception, the TSVs as per gathered from the surveys were compared as shown in figure 6. The results show that the female students tend to be more resilient to warmer conditions and more sensitive to cooler weather in comparison to the male students. In Space 1, a higher percentage of female with "neutral" vote was recorded (52.05%) verses (47.37%) for male. In Space 2, the highest percentages were for the TSV= +1 for the male and female with 39.6% and 40% respectively. Additionally, there is a significantly larger percentage of students voting "worm" and "hot" in Space 2 in comparison to Space 1. This indicates that MRT and air temperature are highly accompanied with change in the thermal sensation of the students. These findings are consistent with what was reported in previous studies [40,41].

According to previous results, a further investigation was made by analyzing the participants' thermal preferences according to the different microclimatic parameters. This facilitated understanding how each climatic parameter affects the participant's overall thermal comfort. In Space 2, most participants preferred a cooler air temperature and mitigated solar radiation with a percentage of 87.3% and 78.48% respectively. In Space 1, "No change" represented the largest portion of the recorded votes across all the examined parameters. However, this was not the case in Space 2. No clear preference was noted for wind speed, relative humidity, the surface temperature.

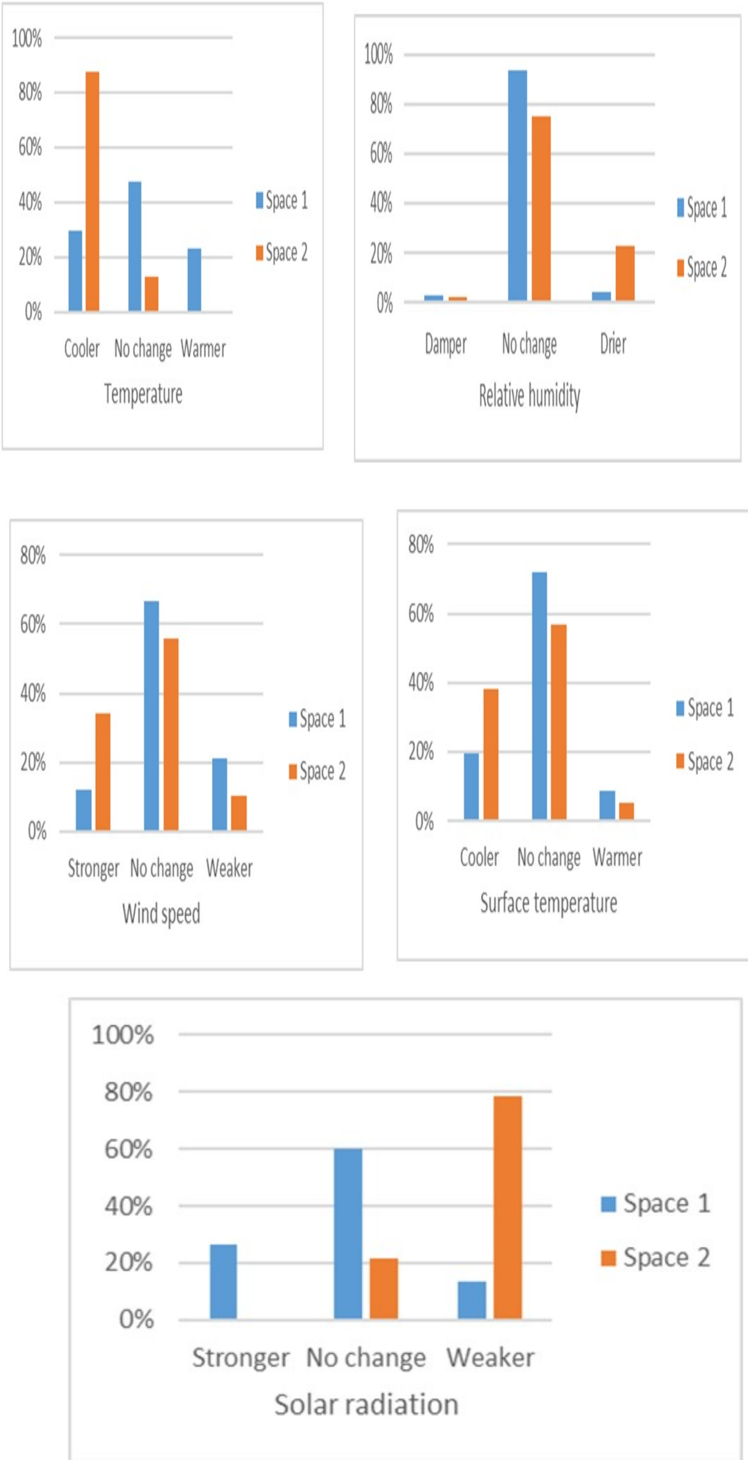


Figure 7: Thermal preferences vote in the moderate seasons in the two spaces, for all the measured climatic parameters: air temperature, wind speed, relative humidity, solar radiation, and surface temperature.

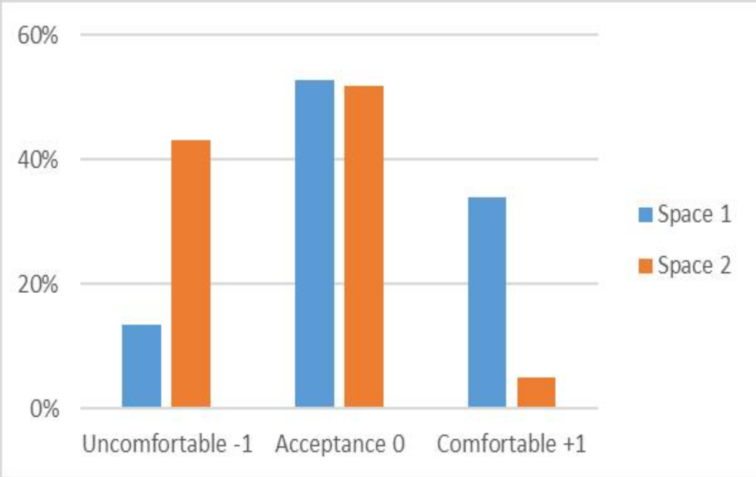


Figure 8: Thermal preferences vote in the moderate seasons in the two spaces for the thermal comfort conditions in general.

Generally, in Space 2 50% felt that the climatic conditions were thermally “acceptable” while 43% felt “uncomfortable”. Conversely, in Space 1, only 16% of the users felt uncomfortable. All the aforementioned results confirm that space 1 has consistently enjoyed improved thermal conditions according to measurements and the users’ perception. Space 1 had no vegetation or greenery within it, it was completely paved while space 2 had the majority of its ground covered with grass and contained a number of trees and palm trees. Hence, manipulating space geometry should be prioritized in comparison to utilization of landscape as it proved to have a significantly stronger influence on outdoor thermal comfort. These findings are in alignment with prior studies that have demonstrated the strong relationship between space geometry and PET [21].

Conclusion

In this experimental study, a comparative analysis was conducted to examine the degree to which outdoor space configuration impacts thermal perception of outdoor space users. The study took place during moderate seasons in 2022 in Giza, Egypt. Measurements for air temperature, relative humidity, wind speed, mean radiant temperature (MRT), and surface temperature were simultaneously taken from two spaces. Space 1 was well configured geometrically but contained no greenery. Space 2 was poorly oriented and less enclosed but 60% of its area was covered by greenery. The sample examined was formulated from 290 participants of students (young adults). Each participant was asked to fill out a questionnaire designed according to ASHRAE 7-point, and [42]. The climatic conditions and the personal qualities of the students (clothing and activity) were all used as inputs to calculate the PET using Rayman. PET calculation represented an objective tactic to estimate the thermal comfort levels in the two spaces, while the surveys was performed to induce the subjective thermal perception of the space users.

According to objective, measurements PET was found to be consistently lower in Space 1 throughout all the examined timings in spring and fall. The subjective evaluations demonstrated that Space 1 was also more thermally comfortable. “Neutral” thermal sensation was the most commonly voted with 50% and 49.15% in spring and fall at space 1 followed by slightly warm with 26.58%, however, in space 2 the slightly warm sensation was the most chosen vote with 26.58% and 44.26% followed by warm at 28% and 40% in spring and fall. The majority of the students in space 1 has consistently chosen “No change” for all the examined climatic parameters. In Space 2, the majority reported to prefer “Cooler” air temperature and more mitigated solar radiation. Hence, it becomes evident through objective and subjective analysis that space 1 was more thermally comfortable than space 2. This indicates that space geometry manipulation has stronger impact on improving the thermal performance of outdoor spaces than landscape design or greenery utilization. These findings can be useful for architects and planners as they design new schemes or transform existing communities. On the other hand, while a significant body of literature was developed to discuss how the physical characteristics of space (like the uses overlooking it or the way its furnished), limited studies investigated how the thermal performance of outdoor spaces may affect the activities and the number of users within it. Future research may tackle this gap. Overall, the findings of this study may be useful for planners and architects who design new schemes or develop existing projects should they prioritize outdoor thermal comfort in their designs.

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