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Outdoor thermal perception in the semi-arid climate of Constantine, Algeria: A field survey during the post-COVID-19

Afef Ouis [a,*], Nassira Benhassine [a], Fatih Canan [b]

[a] Laboratory of Bioclimatic Architecture and Environment (ABE), Faculty of Architecture and Urban Planning, University of Constantine 3 Salah Boubnider, Constantine, Algeria

[b] Department of Architecture, Faculty of Architecture and Design, Konya Technical University, Akademi Mah, Yeni İstanbul Cad, No:235/1 Selçuklu, Konya, Turkey

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ABSTRACT

The purpose of the paper was to assess pedestrians' thermal perception, in the semi-arid climate of Constantine, Algeria, with particular emphasis on the protocols implemented in public spaces during the post-COVID-19. Three outdoor public spaces were selected in August 2021 to conduct a field study involving 254 respondents, randomly assigned. The adopted approach combined objective and subjective assessment, as well as numerical simulations using ENVI-met. Accordingly, microclimate monitoring and a questionnaire survey were carried out simultaneously from 7 a.m. to 7 p.m. in each study site. A strong association was found between the combined microclimate parameters (objective variables) and thermal sensation of the surveyors with ($R^2 = 0.74$). Besides, Kruskal-Wallis *H* test revealed that the subjective thermal sensation was significantly influenced (*p-value* <0.05) by thermal history and purpose of visit (subjective variables). Most interviewees preferred 'move to shade' measure as a remedial behavior to reduce their thermal discomfort. Further, a neutral temperature of 22.7 °C PET was obtained by a linear regression between the Mean Thermal Sensation Votes (MTSV) and Physiological Equivalent Temperature (PET), the comfort range was estimated between 18.6 °C ≤ PET≤ 26.8 °C during summer. Regarding the COVID-19 pandemic effects, the Chi-square test suggests that the frequency of pedestrian visits was statistically independent of the imposed pandemic measures. However, the planned activities were affected by social distancing and the use of face masks increases pedestrians' thermal discomfort. Overall, the study highlights the significance of environmental and non-environmental factors to improve outdoor thermal comfort, and ensure human well-being.

1. Introduction

Outdoor public spaces including squares, plazas, esplanades, green parks, and sidewalks among others play a vital role in promoting urban life, health and well-being. Attractive and well-designed urban spaces with favorable microclimate would intrigue the residents and the visitors of the city to engage in different recreational, social, and cultural activities [1]. As demonstrated in several studies [2–7], thermal comfort in outdoors is a key element that influences the quality and the usage of urban spaces. Thus, understanding and assessing outdoor thermal comfort is crucial and challenging.

Human's thermal perception and comfort in outdoor environments are highly affected by the microclimate parameters. However, their assessment is not constantly dependable on the objective factors (air temperature, air velocity, relative humidity, and solar irradiation) [8]. The subjective factors such as thermal adaptation and social factors (thermal history and expectancy, behavioral and psychological aspects) play a major role in influencing human thermal sensations and the utilization of outdoor spaces [9,10]. As stated by Chen and Ng [11], the 'state of mind' as well as the 'state of the body' determines how people really use urban spaces.

Subsequently, numerous methods have been employed in the last decades, to identify the drivers that determine thermal comfort and to evaluate the thermal environments for humans; they can be classified into two primary approaches. Qualitative studies involve interviews, observations, and questionnaire surveys, while quantitative approaches rely on, in-situ measurements or/and numerical simulations [12]. In fact, with the advancement of methods in both domains of urban climatology and bio-meteorology [13–17], the quantitative methods started to progress and gained more interest. The study by Nikolopoulou

* Corresponding author.
E-mail address: afef.ouis@univ-constantine3.dz (A. Ouis).

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et al. [18] conducted in urban open space (seating area) in Cambridge City was one of the first studies to tackle human thermal behavior and its methodology influenced abundantly the succeeding studies in this field.

Several studies [19–25] used different thermal indices and assessment scales to estimate thermal perception across diverse climatic zones. Potchter et al. [26] argued that out of the 165 bio-meteorological indices, only four indices (PMV, PET, SET*, UTCI) are commonly applied for human thermal assessment in outdoor environments. The Predicted Mean Vote (PMV) introduced by Fanger [27] and the Standard Effective Temperature (SET*) as defined in the paper of Gagge et al. [28], were developed as indices for indoor thermal comfort evaluation. Whereas, the thermo-physiological indices such as the Physiological Equivalent Temperature (PET) by Refs. [29,30] and the Universal Thermal Climate Index (UTCI) recently developed by Blazejczyk et al. [31] were originally designed to describe the association between the outdoor thermal conditions and the people thermal sensations. Hence, the vast number of thermal indices and the lack of a common framework or agreed protocol to assess human thermal comfort in outdoors led researchers from Italy Golasi et al. [32] to propose a Global Outdoor Comfort Index (GOCI), as an attempt to unify and standardize the empirical outdoor thermal indices. Whereas, other researchers introduced local indices such us Mediterranean Outdoor Comfort Index (MOCI) by Salata et al. [33] or Turkish Outdoor Comfort index (TOCI) by Canan et al. [34], more adapted to assess thermal perception for a specified population.

Despite the growing number of human bio meteorological research that have been conducted in one or different sites or even large-scale projects, the sudden outbreak of COVID-19 brought unprecedented issues and challenges to the study of outdoor public spaces, where new measures have been imposed to prevent the viral spread and address the public health threats. Specifically, (1) social distancing referred as “physical distancing”, implying space of at least six feet between individuals outside [35]. To accommodate safe distance in urban spaces, Hassan and Megahed [36] assessed the layout and arrangements of nine urban seating models using 3D computational fluid dynamic (CFD). (2) Mandatory face mask in public places, served for two purposes: protecting the wearer and preventing the spread of the virus from infected person [37]. Face mask was considered as the main and cost effective measure to control and mitigate the COVID-19 transmission among people [38]. (3) Lockdown and curfew restrictions affected peoples’ activity patterns in the outdoors and space usage [39,40]. However, a city based model to simulate the COVID-19 early spread in China, found that implementing lockdown was more effective in containing COVID-19 than decreasing the population mobility [41]. While this is the case, a comparison in the pedestrian mobility between the pre-pandemic and post pandemic period in an Iranian municipality square showed a strong tendency towards social places after the lockdown [42].

According to the systematic review of Han et al. [43], after the outbreak of coronavirus disease the main topic of investigation was site attendance. In Norway, Certain alterations had been observed such as, the increase in recreational activity and the shift from housing and commerce districts towards urban green parks and nature reserves during lockdowns [44]. The most popular recreation locations were found adjacent to forests, semi-natural sectors, and housing areas reasonably close to the respondents’ homes, as per to spatial analysis performed in Finland [45]. In line with this, an online survey was carried out in six different countries to assess the advantages of urban green space usage during the social isolation [46]. Whereas, a questionnaire and field observations in two city parks of Jeddah were used, to explore the activity behavior, attitude, and perception of city parks in Saudi Arabia all through the COVID-19 pandemic [47]. Further, some aspects of outdoor activities such as recreational walking and physical activities have become even more essential because of the pandemic’s impacts [48–50]. This global crisis asserted the importance of outdoor public spaces for physical health and psychosocial wellness of the citizens [51], thus, it is encouraging architects and urban planners to rethink how they design more resilient public places that meet the changing needs of the population and promote the wellbeing [52].

Therefore, during the post-pandemic conditions in summer 2021, three outdoor public places were selected to conduct a research about pedestrians’ thermal perception within a semi-arid climate of Constantine, Algeria. Given that existing research studies have commonly analyzed human thermal sensations in different climates, except the semi-arid environments in North African regions. To this end, the first crucial topic of this research was to assess the subjective thermal perception and compare it with the computed thermal comfort index (PET), the effects of micro-meteorological parameters and thermal adaptations on human thermal sensations were also investigated by combining in-situ measurement, questionnaire survey, and numerical simulations. In combination with the first focus, the second topic of importance was to explore from a pedestrian perspective, the effects of the new measures enforced by the COVID-19 pandemic, namely, the face masks; social distancing; and curfew on thermal comfort and overall usage of outdoor places, by means of statistical analysis.

2. Methodology

The research method consists of three main phases, the initial phase, involved concurrent microclimate measurements and a questionnaire survey carried out from 7 a.m. to 7 p.m. (12 h in a row) on typical hot summer days at each study site. It is important to mention that, the data acquisition was constrained by the COVID-19 curfew regulations (8 p.m.–6 a.m.), which mandated that no fieldwork could extend beyond 7 p.m., and as such, the data collection was curtailed accordingly. The subsequent phase included numerical simulations using ENVI-met software to map outdoor thermal comfort, while RayMan software computed the physiological equivalent temperature (PET) for each respondent. Lastly, the dataset obtained from the field study was inserted and analyzed in SPSS software. To Sum up, the diagram depicted in Fig. 1 and the following sections explain in more detail the research methodology.

2.1. Geographic context

The study was conducted at three outdoor public places; *Si El Haoues* place (C1), *la Bréche* Esplanade (C2), and *Hadj Ahmed Bey* place (C3) located in the historic city center of Constantine, Algeria, refer to Fig. 2. Constantine is situated in the northeast of Algeria, between 7° 23′ E longitudes, 36° 17′ N latitude, and has an altitude of 687 m above sea level. In order to understand better the urban morphology of the studied sites and correlated with the thermal environment, the sky view factor (SVF) was calculated at each site using hemispherical photos [53]. Despite the compact layout of the historical center, the SVFs varied from 0.89 to 0.95 at the selected outdoor public spaces Fig. 3, due the existence of mid-rise buildings with similar heights on both sides of the sites and the lack of vegetation.

Being a part of the (BSk) zone Constantine is classified as a cold semi-arid climate with hot dry summers, and cold rainy winters as identified by the Köppen-Geiger climate map [54]. As follows from Fig. 4, the hot season spans from June to late September, the mean maximum air temperature varies from 32.2 to 38.6/38.1 °C between September and July/August. Moreover, solar radiation over this city is relatively high, with clear skies and an abundance of sunlight covering a considerable part of the day [55]. While the maximum range for the cold season runs from 13.9 to 14.4 °C between January and December. The mean air temperature peaks at 29.2 °C in July and gets low to 7.6 °C in January. A transitional season covers the rest of the months (October/November and April/May) ranging from 12.6 °C to 19.6 °C for the mean air temperature. Mean relative humidity throughout the year ranges from 87 % to 53 % between December/January and July.

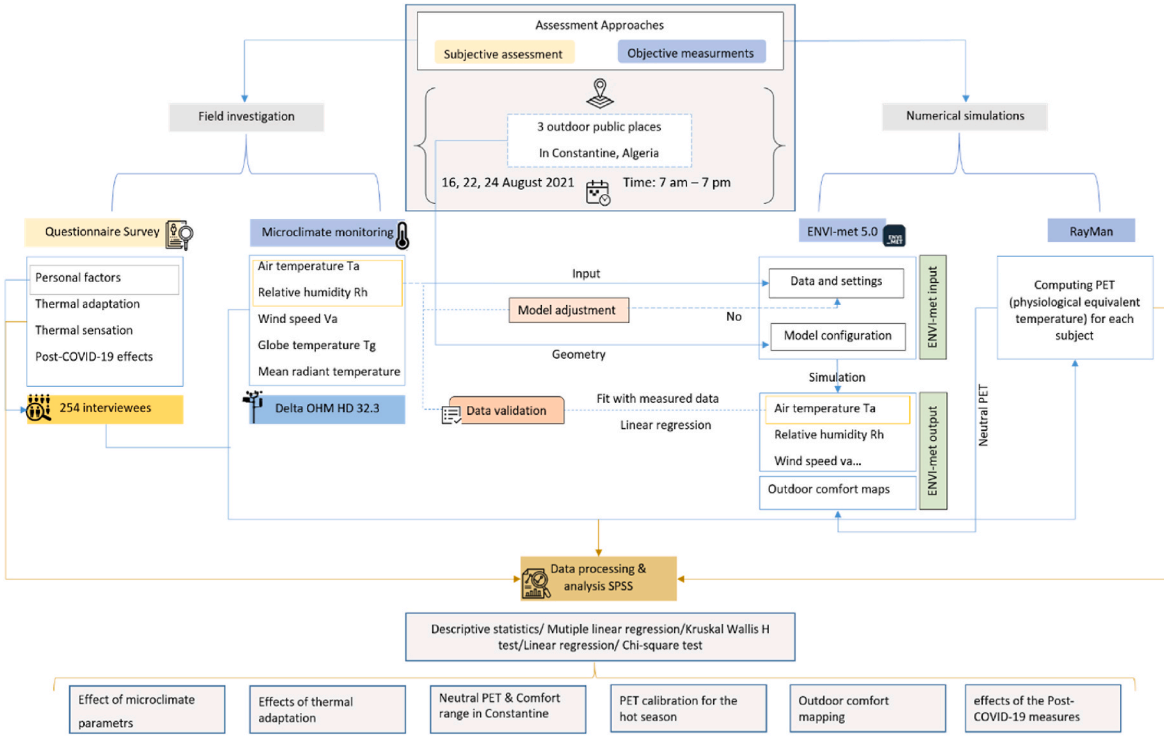


Fig. 1. Methodological framework of the research study.

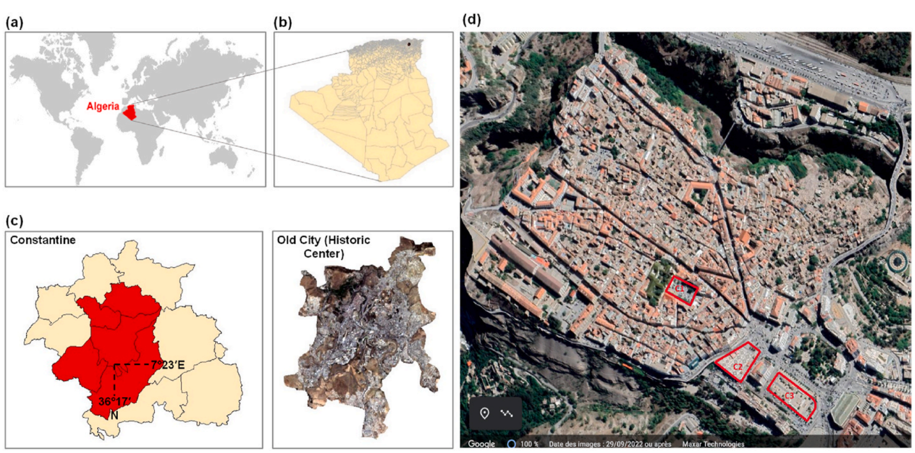


Fig. 2. Geographic context of the study sites. (**a**) Algeria in the world, (**b**) Location of Constantine, (**c**) Study area, (**d**) General view of the selected sites (Google Earth).

2.2. *Microclimate-monitoring*

During the hot season in August 2021, the micro-meteorological parameters were measured simultaneously, an hourly interval was recorded (to coincide with the ENVI-met input/output time scale) using Delta OHM HD 32.3 instrument. The accuracy of the instrument was in compliance with the recommendations of ISO 7726 (1998) and ASHRAE 55 (2010) Standards [57,58], the probes were mounted on a tripod at the height of 1.1 m above the ground (see Fig. 5a), and it was shielded from the direct solar irradiation. The Delta OHM HD 32.3 instrument was supplied with a globe thermometer probe (TP3276.2, globe diameter = 50 mm) to gauge globe temperature Tg (°C); a temperature probe (TP3207.2, with a sensitive sensor Pt100) for air temperature Ta (°C) recording. While relative humidity Rh (%) was measured by a combined probe (HP3217.2, capacitive sensor); and the air velocity Va (m/s) by an omnidirectional hot wire probe (AP3203.2, NTC 10Kohm), refer to Fig. 5b and Table 1 for more details. Whereas, the mean radiant temperature T_{mrt} (°C) was derived from the equation of Thorsson et al. [59]:

$$T_{mrt} = \left[\left(T_g + 273.15\right)^4 + \frac{1.1 \times 10^8 \times V_a{}^{0.6}}{\left(\varepsilon \times \mathrm{D}^{0.4}\right) \times (\mathrm{Tg} - Ta)} \right]^{0.25} - 273.15 \quad (1)$$

where Tmrt-mean radiant temperature (∘C);
Tg Globe temperature (∘C);
Ta Air temperature (∘C);
V Air velocity (m/s);
ε Globe emissivity (0.95);
D Globe thermometer diameter (50 mm).

2.3. *Questionnaire survey*

Considering the research objective that is to gather data about

Fig. 3. Site configuration. (**a**) View photos of the selected study sites, (**b**) Fish-eye photos and Sky view factor (SVF) values.

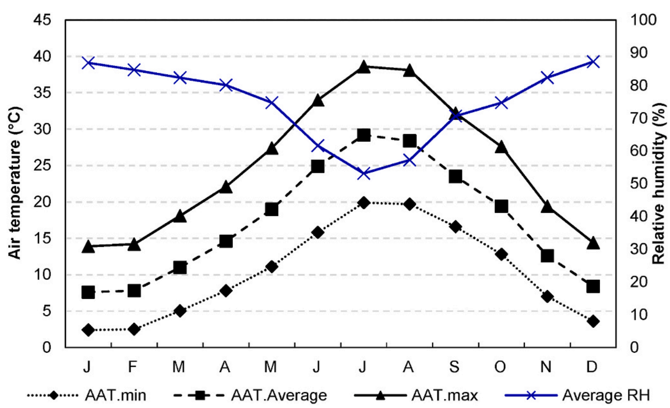


Fig. 4. Annual average of air temperature and relative humidity in Constantine [56].

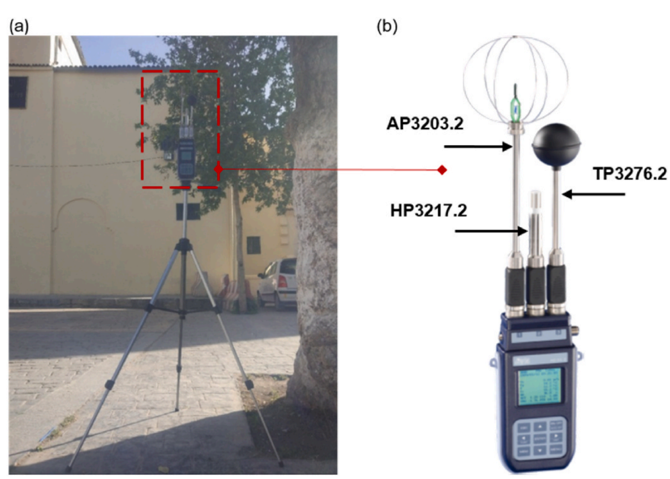


Fig. 5. (**a**) Microclimate measurements, (**b**) Delta OHM 32.3 instrument (Operating manual).

subjective thermal perception and the effects of the post-COVID-19 pandemic on the use of outdoor urban spaces. A questionnaire was elaborated based on similar studies [60,61]. Furthermore, a pre-investigation was conducted to refine the type of questions and format the survey in a concise simple way to be accomplished within 8–10 min. Based on the interviewees' feedback a few corrections were made mainly on the length of the questionnaire.

Through a random process, the respondents at each survey site were designated, and administered a 'point in time' questionnaire. The total obtained questionnaire was 254 (see Table 2), with the sample size being subject variation due to a range of factors: hot weather, time constraints, and pandemic-related precautions. To sum up the questionnaire was structured into three main sections refer to Appendix A, with the first section divided in two categories of questions. The first category requested personal data, such as age; gender; height; weight; and place of residence; while the type of clothing; and the levels of activity were approximated using (ISO 9920) [62], and (ISO 8996) [63] respectively. The second category gathered information on the respondents' thermal adaptation.

Followed by Likert scale questions were developed in conformity with (ASHRAE Standard 55) [58] to assess thermal sensation and satisfaction votes. For that reason, a 7-point scale ranging from cold (−3) to hot (3) was used to rate thermal sensation votes namely (TSV). In the same way, thermal satisfaction votes were evaluated from very dissatisfied (−3) to very satisfied (3).

The last section emphasized how the COVID-19 restrictions, such as social distancing, mandatory face masks, and curfews affected pedestrian's behavior and attendance at the three distinct study sites. Relevant inquiries regarding the frequency of visits, the planned activities (resting; walking; social interactions; and other), and the thermal perception of individuals when wearing a face mask during the post-pandemic period were collected and analyzed for their scientific significance.

2.4. Numerical simulations

This study employed two software, RayMan, to compute the thermo-physiological index (PET) for each respondent. This numerical index has been commonly used as a means of evaluating outdoor thermal comfort [17]. Expressed in degrees Celsius (°C), and based on a model that takes into account several inputs data for running RayMan model. Such as air temperature, mean radiant temperature, relative humidity, and air velocity, as well as, the metabolic activity and clothing insulation parameters [64].

The second software was ENVI-met (V5.0), which is a three-dimensional microclimate software based on the laws of

Table 1
Characteristics of Delta OHM 32.3 instrument.

Climatic parameters	Probe type	Accuracy	Resolution	Range
Air temperature	Combined probe TP3207.2R, thin film Pt100	Class 1/3 DIN ±0.1 °C	0.1 °C	−40 °C to +80 °C
Relative humidity	Combined probe HP3217.2R, capacitive sensor	±1.5 % (0 … 90 % Rh) ±2 % (90 … 100 %)	0.1 %	0 %–100 %
Air velocity	AP3203.2 Omnidirectional hot wire probe, NTC 10Kohm	±0.2 m/s (0.1 ÷ 1 m/s) ±0.3 m/s (1 ÷ 5 m/s)	0.01 m/s	0.1 m/s to 5 m/s
Globe temperature	TP3276.2 globe thermometer probe (Ø = 50 mm) Pt100	Class 1/3 DIN ±0.1 °C	0.1 °C	−10 °C–100 °C

Table 2
Field measurement dates, time, and number of collected questionnaire.

Site	Date	Time	collected questionnaire
Si El Haoues place (C1)	16 August 2021	7 a.m.–7 pm	103
La Brèche Esplanade (C2)	22 August 2021	7 a.m.–7 p.m.	40
Hadj Ahmed Bey place (C3)	24 August 2021	7 a.m.–7 p.m.	111

computational fluid dynamics (CFD). ENVI-met can simulate all the microclimate parameters; with a detailed modelling design including; buildings, vegetation, different soil surfaces, and materials. Therefore, it can assess the effects of urban design, and green spaces on the environmental conditions and human thermal comfort [65]. Three typical summer days from August were selected 16th, 22nd, and 24th, 2021. Since they were the field survey days for *Si El Haoues* place (C1), *la Bréche* Esplanade (C2), and *Hadj Ahmed Bey* place (C3) consecutively. The simulation was configured with the duration of 24 h (one day) starting at 6 a.m., while only the output of 12 h (7 a.m.–7 pm) was considered for assessment (which aligns with the duration of the field survey). All the necessary inputs were defined before launching the simulation process. The different obtained data were analyzed; the simulation outputs were then visualized to generate 2D outdoor comfort maps using the PET index.

2.4.1. ENVI-met model configuration

In the current study, three outdoor public places mentioned above were digitized within a grid-based tool 'Space' as illustrated in Table 3; the size of the grid resolution was set to 3 × 3 m. As for the vertical grid generation, it was three times higher than the highest building in our model. Then, to achieve faster simulations and avoid divergence, the telescoping mode was activated with a 10 % factor. Resulting in area input files of 330 × 300 m (*Si El Haoues* place C1), 390 × 390 m (*la Bréche* Esplanade C2), and 270 × 240 m (*Hadj Ahmed Bey* place C3). Moreover, building materials, soil surfaces, and other physical features were specified in the 'database manager', and the vegetation species and size were configured in 'Albero'. In preceding ENVI-met modelling studies [66,67], nesting grids were added at the boundaries of the model area to augment the numerical stability of the simulation.

2.4.2. ENVI-met data validation

To validate the ENVI-met results, the linear regression approach has been widely used in recent studies [67–69]. To achieve that, the collected microclimate variables (air temperature, relative humidity, or the mean radiant temperature) were compared to the corresponding simulated parameters. Similarly, in this study, the hourly variation of measured air temperature in the three sites was fitted to the modelled air temperature as depicted in Fig. 6. The results showed a strong correlation between the measured and simulated air temperature of the three studied areas where R^2 ranges from – 0.85–0.92–.

Despite the similar pattern depicted in Fig. 6, the ENVI-met model overestimated the air temperature in both early and late afternoon in all studied sites and underestimated the air temperature in the midday. Thus, two metrics were calculated to evaluate the performance of the model, the root mean squared errors (RMSE) and the index of agreement (d) developed by Ref. [70]. The RMSE values for the three sites varied from 1.6 °C (C3), 1.8 °C (C1) to 2.8 °C (C3). These discrepancies between measured and simulated data may be due to the high temperature in the study sites, which may have led to simulations and meteorological errors. Comparing the RMSE values regarding air temperature validation highlighted in Table 4, it is evident that the results presented in this study 1.65– 2.8–1.8 °C for the selected sites demonstrate a relatively better accuracy when contrasted with the observed values 2.9–4.8 °C conveyed by Refs. [71,72] in turn. Additionally, the ENVI-met model performance in a recent paper by Nasrollahi et al. [73] yielded a RMSE of 2.8 °C, aligning with the highest RMSE calculated for *la Bréche* Esplanade (C2). In similar research endeavors [66,74] the RMSE values 1.4–1.2 °C obtained are slightly lower than our values 1.6–1.8 °C suggesting a comparable level of precision. Furthermore, the degree of agreement between the recorded and simulated air temperature in the research locations is nearly a perfect match where the calculated d is 0.99, indicating that the results from the ENVI-met model predicted the observed air temperature very well. Hence, it is possible to assert that by properly selecting the model input parameters with the accurate model configuration, the resultant output data is closely aligned with the experimentally measured values.

2.5. Data processing and analysis

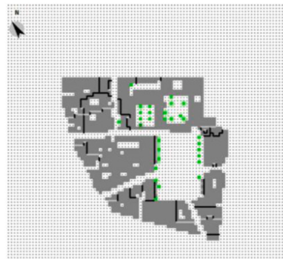
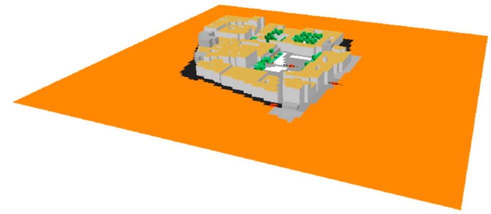
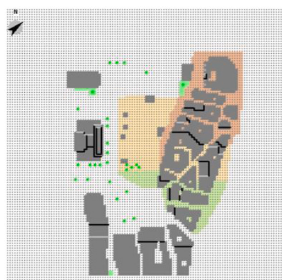
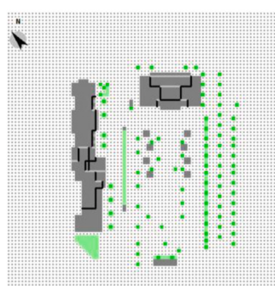
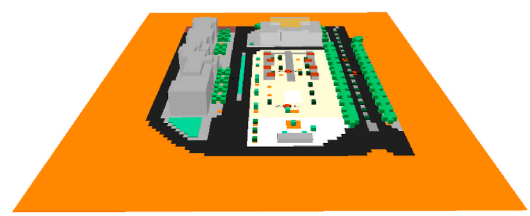
In this paper, statistical methods were used to assess the different collected data by SPSS (Statistical package for the social sciences) software, version 25.0. Firstly, the demographic characteristics of the sample were summarized to measure the variability of the collected data. Likewise, a summary of the microclimate data (minimum, maximum, mean, and standard deviation) for each study site was obtained using descriptive statistics. Secondly, the percentage distribution of thermal response votes (sensation and satisfaction) in each site was analyzed.

Following that the influence of the microclimate parameters (objective factors) on the surveyors' thermal sensations (TSV) was examined using multiple regression analysis. Whereas, a non-parametric Kruskal-Wallis *H* test was utilized to assess the effect of the subjective factors such as purpose of visits; exposure time; previous activities, and short-term thermal history; as well as the adaptive behavior on the interviewees' thermal sensations.

Furthermore, a linear regression was performed to determine the interrelation between the subjective TSV and the computed PET, and examine how the thermal sensation of interviewees varied at different grades of physiological stress. The neutral temperature defined as the comfort temperature at which a person feels neither hot nor cold [27] was also estimated by finding the linear regression intercept. Then, high-resolution 2D maps of PET for the selected study sites were obtained using the ENVI-met software.

Finally, another nonparametric test namely Chi-Square test, was used to analyse data obtained from the post-COVID-19 section. The

Table 3
ENVI-met geometric models' of the selected sites.

Site	2D model in ENVI-met	3D model in ENVI-met
Si el Haoues place (C1)		
La Bréche Esplanade (C2)		
Hadj Ahmed Bey place (C3)		

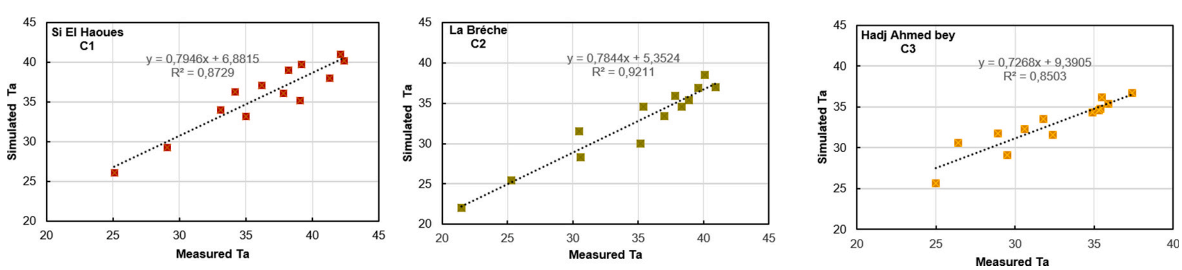


Fig. 6. Relationship between simulated air temperature and measured air temperature at the selected sites (the data displayed are hourly averages).

collected data pertaining to various COVID-19 measures (facemask usage; social distancing; curfew adherence) from the interviewees was examined. In order to determine if there is a significant influence on the pedestrians' thermal perception and their utilization of outdoor public spaces during the post-pandemic period. At a significance level of (p-value 0.05), all of the provided data followed the 95 % confidence interval.

3. Results and discussion

3.1. Socio-demographic characteristics

This study includes 254 respondents, 68.9 % were men and 31.1 % were women, for cultural and social reasons men outnumber women in outdoor public spaces of Constantine. As given in Table 5, most of the interviewees were young people, the age ranges 21–35 years had the greatest frequency of respondents in this investigation (29.9 %) followed

Table 4
Diverse metrics for validating ENVI-met results in prior studies.

Studies	City	R^2	RMSE	d
Present study	Constantine	0.87[a]–0.92[b]–0.85[c]	1.65[a]–2.8[b]–1.8[c]	0.99
Qaid and Ossen [75]	Putrajaya, Malaysia	0.69	1.82	0.60
Hedquist and Brazel [71]	Phoenix, USA	0.89	2.9	0.79
Song and Park [72]	Changwon, Korea	0.52	4.83	–
Middle et al. [66]	Phoenix, USA	–	1.41[d]–1.81[e]-2[f]	0.99[d]–0.98[e]–0.97[f]
Salata et al. [76]	Rome, Italy	0.88	1.89	0.91
Heris et al. [74]	Denver, USA	–	1.2[g]–2.4[h]	0.97[g]–0.98[h]
Nasrollahi et al. [73]	Ahvaz, Iran	0.86	2.8	0.91

[a] *Si El Haoues* place C1.
[b] *la Bréche* Esplanade C2.
[c] *Hadj Ahmed Bey* place C3.
[d] Mesic.
[e] Oasis.
[f] Xeric.
[g] Lakewood.
[h] Boulder.

Table 5
Demographic characteristics of the surveyed participants.

Variables		Frequency (N)	Percent (%)
Gender	Male	175	68.9
	Female	79	31.1
	Total	254	100
Age range	≤20	59	23.2
	21–35	76	29.9
	36–45	44	17.3
	46–55	33	13.0
	56–65	29	11.4
	>65	13	5.1

by participants under 20 (23.2 %). It is imperative to note that gender and age-related impacts on outdoor thermal sensation was examined in different studies. Certain investigations Shooshtarian and Ridley [77] yielded inconclusive results regarding the influence of gender and age on thermal sensation, while contrasting studies Krüger and Rossi [78] and Pantavou et al. [60] revealed statistically significant outcomes. In order to estimate the clothing insulation for the respondents, a pre-arranged checklist for the type of attire worn was provided (check Appendix A). The mean values for clothing insulation for male and female interviewees were found to be 0.51 clo and 0.70 clo correspondingly.

3.2. Microclimate data

The recorded microclimate data at different survey sites are summarized in Table 6. Overall, the outdoor thermal environment during the measurements was hot and dry with high air temperature, reaching 42.4 °C (SD = 5.0 °C) at *Si el Haoues* place (C1), 40.9 °C (SD = 6.0 °C) at *La Bréche* Esplanade (C2), and 37.4 °C (SD = 3.9 °C) at *Hadj Ahmed Bey* place (C3). Also, the highest logged for the mean radiant temperature was 79.2 °C (SD = 17.2 °C) registered at La Bréche place (C2). While, the mean relative humidity was averaging from 20.0 %, 17.7 %, and 35.8 % respectively. Distinct discrepancies between the sites were observed; open sites with no obstructions such as the esplanade *La Bréche* (C2) (SVF = 0.94) and *Hadj Ahmed* place (C3) (SVF = 0.95) were windier. With a means record of 2.3 m/s (SD = 1.1 m/s) and 1.6 m/s (SD = 0.9 m/s) correspondingly, then the centrally located site like *Si el Haoues* place (C1) where the mean wind speed was 0.7 m/s (SD = 0.6 m/s).

Table 6
Summary of the microclimate data for each survey site.

Site		Ta (°C)	Rh (%)	Va (m/s)	Tg (°C)	Tmrt (°C)
Si El Haoues *place (C1)*	Mean	36.3	20.0	0.7	40.2	47.4
	Minimum	25.1	12.5	0.0	25.4	26.6
	Maximum	42.4	37.9	2.0	51.8	65.0
	SD	5.0	7.1	0.6	7.7	12.8
La Bréche *esplanade (C2)*	Mean	36.3	17.7	2.3	38.2	54.0
	Minimum	21.5	10.6	0.9	21.6	22.2
	Maximum	40.9	35.4	5.2	47.2	79.2
	SD	6.0	7.7	1.1	7.9	17.2
Hadj Ahmed Bey *place (C3)*	Mean	32.2	35.8	1.6	33.8	41.5
	Minimum	25.0	23.3	0.5	25.3	26.0
	Maximum	37.4	61.4	3.3	40.3	66.1
	SD	3.9	11.8	0.9	4.9	11.2

3.3. Subjective thermal responses

Across the selected study sites, a certain similarity was detected in the thermal sensations of the respondents as shown in Fig. 7a. The sensation of 'hot' (TSV = 3) was predominant with 64.1 %, 70 %, in *Si El Haoues* place (C1); and *La Bréche* Esplanade (C2). Though 50.5 % of the respondents in *Hadj Ahmed Bey* place (C3) choose warm (TSV = 2). As can be seen from Fig. 7b, only 9.1 % experienced 'neutrality' (TSV = 0) and 1.2 % felt 'slightly cool' (TSV <0). The highest percentage (47.2 %) of the interviewees voted for 'hot', followed by interviewees choosing 'warm' and 'slightly warm' (TSV> 0), accounting for 32.7 % and 9.8 % correspondingly. Since the survey was conducted on hot sunny days, it was estimated to detect a high percentage of 'hot' and 'warm' votes in the study sites. As follows from Table 7 that relates thermal conditions of the respondents expressed by (TSV) with average measured air temperature (Ta). It can be observed that in most cases when the actual measured air temperature increased the respondents expressed more thermal discomfort (TSV> 0). Fig. 8a display the percentage distribution of thermal satisfaction votes, 'very dissatisfied' was the lowest (5 %) at (C2) Esplanade *La Bréche* due perhaps to the high air speed, and the highest thermal dissatisfaction (79.6 %) belonged to (C3) *Si El Haoues* place because of the intensive solar radiation and the low airspeed. From Fig. 8b, a total of 77.5 % votes including (very dissatisfied; dissatisfied, slightly dissatisfied) was reported by the interviewees, a minority of 5.5 % and 5.9 % felt 'slightly satisfied', and 'satisfied' with their thermal environment.

3.4. Objective and subjective variables effects

3.4.1. Microclimate parameters

To explain the variation in thermal sensation votes (TSV), the predictors (independent) variables included air temperature, mean radiant temperature, relative humidity, and air velocity as in Refs. [79,80]. In alternative studies [81,82] the evaluation of thermal sensation by microclimate variables involved solar radiation rather than the mean

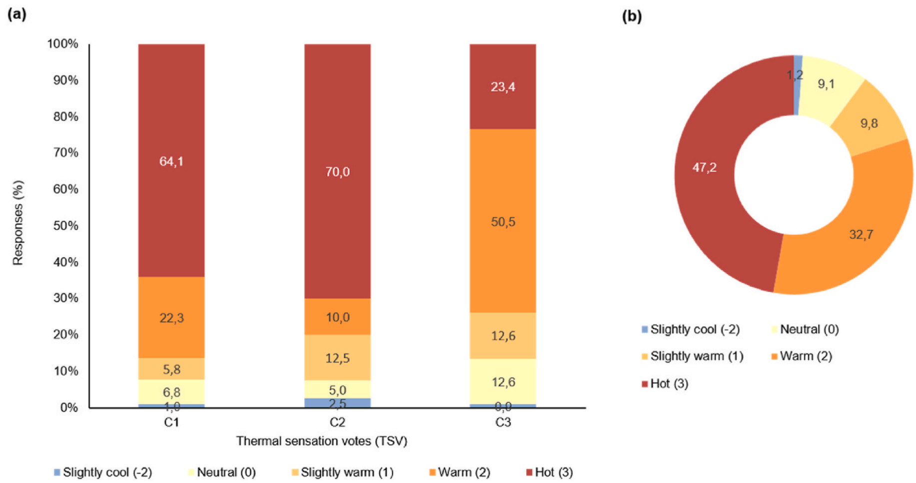


Fig. 7. (**a**) Percentage distribution of thermal sensation votes in the selected sites, (**b**) Total votes of the responders' thermal sensation.

Table 7
Comparison between TSV of the respondents and the measured Ta at different sites.

Site	Thermal sensation votes (TSV) slightly cool	neutral	slightly warm	warm	hot
(C1)[a]	25	26.4	29.1	32.3	38.8
(C2)[b]	21.5	26	27	26.7	37.2
(C3)[c]	25	26.1	26.4	31	34.2
Total votes	23.8	26.2	27.5	30	36.7

radiant temperature. The thermal sensation votes (TSV) was significantly related to the microclimate variables, F (4,249) = 180.953 (p-value <0.0005), with a coefficient of determination of $R^2 = 0.74$ (refer to Appendix B, Table B.1). It points out that this model cannot explain 26 % of the variation in TSV. This strong positive association between the combined microclimate parameters (Ta, Tmrt, Rh, Va) and the surveyors' thermal sensation (TSV) was also confirmed by the regression coefficient R = 0.863. According, to the table of coefficients of the *t*-test values (refer to Appendix B, Table B.2) the prediction equation of thermal sensation during summer time in Constantine can be developed as follows:

$$TSV = -4.946 + 0.153Ta + 0.027Tmrt + 0.012Rh + 0.143Va \quad (R^2 = 0.74) \tag{2}$$

The analysis showed that all the independent variables contributed significantly to the model. Besides, it was revealed that air temperature (Ta) was the most significant parameter that influenced substantially the respondents' thermal sensations. These results are generally in accordance with prior research conducted in the Mediterranean climate [83], where air temperature and solar irradiation were the most significant parameters that affect pedestrians' thermal sensation and the use of outdoor urban spaces.

3.4.2. Thermal adaptation

3.4.2.1. Purpose of visit. The purpose of visit responses was classified into three categories: working, resting/meeting other people and passing by. The majority (52.8 %) came to the public open spaces for rest and meetings, and only a few people (7.9 %) were there for working in the small coffee shops and fast food booths. The Kruskal-Wallis *H* test resulted in a significant difference (p-value = 0.0001) for the various purposes, suggesting that the reason of the visit influenced the subjects' thermal sensations. Similar results were found by Johansson et al. [84]

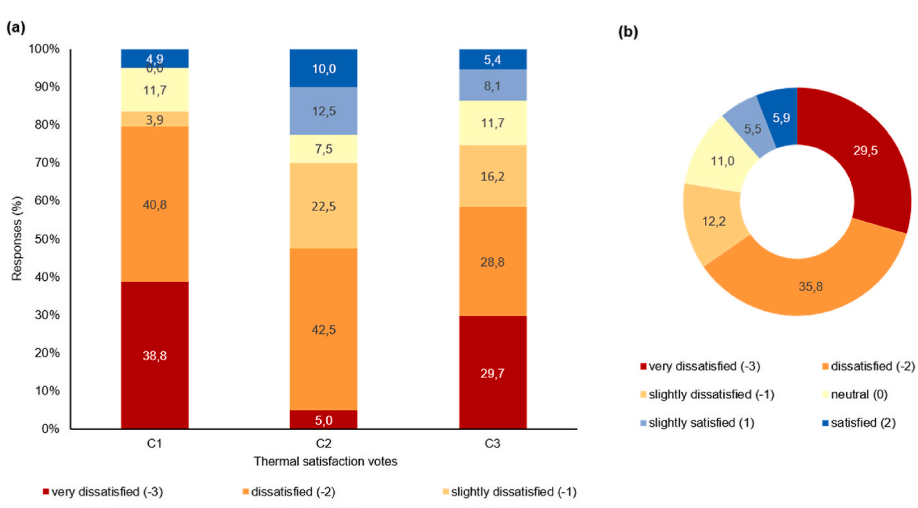


Fig. 8. (**a**) Percentage distribution of thermal satisfaction votes in the selected sites, (**b**) Total votes of the responders' thermal satisfaction.

in Guayaquil, Ecuador, where people who were out at the interview place for meetings accepted higher SET* (31 °C) than the ones who were just passing by (28 °C).

3.4.2.2. Exposure time. Although most of the respondents were visiting the study sites for resting/meeting other people, it should be noted that they stayed on average 5–30 min (39 %); followed by 10.2 % resting for more than 30 min and merely 2 % hang around for more than 1 h (refer to Fig. 9). The Kruskal-Wallis *H* test revealed no significant disparity (p-value = 0.119) for the interviewees' exposure time. In agreement with the results of Yang et al. [85] the thermal sensation of the respondents was not dependent on the different exposure time.

3.4.2.3. Previous activities and short-term thermal history. In agreement with the results of a seasonal investigation conducted in the high dry climate of Arizona, USA [86], the preceding activities (sitting, standing relaxed, or walking) carried out by the responders did not affect their thermal sensation. The Kruskal-Wallis *H* test indicated that while subjective thermal sensation was not statistically distinct for previous activities (p-value = 0.187), it was statistically different for respondents short-term thermal history (p-value <0.05). Over 24 % of the interviewees transitioned from indoor to outdoor environments in the last (15–30 min) prior to completing the survey, the rest (76 %) stayed outdoors.

3.4.2.4. Adaptive behaviour. The respondents answered one question: 'if you feel excessive heat in this place, what measures would you choose?' four kinds of measures were provided in the survey (refer to Appendix A, question 12). Fig. 10 illustrates the cross-tabulation analysis of responses percentage and surveyors' gender. The results indicate that both males and females (49.2 %) preferred 'move to shade trees/shelter' measure to decrease their thermal discomfort. However, they differed in their second choice of measure, for males it was 'drinking beverages' (16.1 %), while females' choice was 'Nothing/leave the place' (9.8 %). Only a few males (2.4 %) picked the adaptive response 'reduce clothing', no females choose the latter response, which may be ascribed to the fact that the degree of garments was already decreased due to the hot weather and cannot be minimized beyond that for cultural reasons. Based on the Kruskal-Wallis *H* test, there is a significant difference in the respondents' thermal sensation (p-value <0.05). Since the behavioural

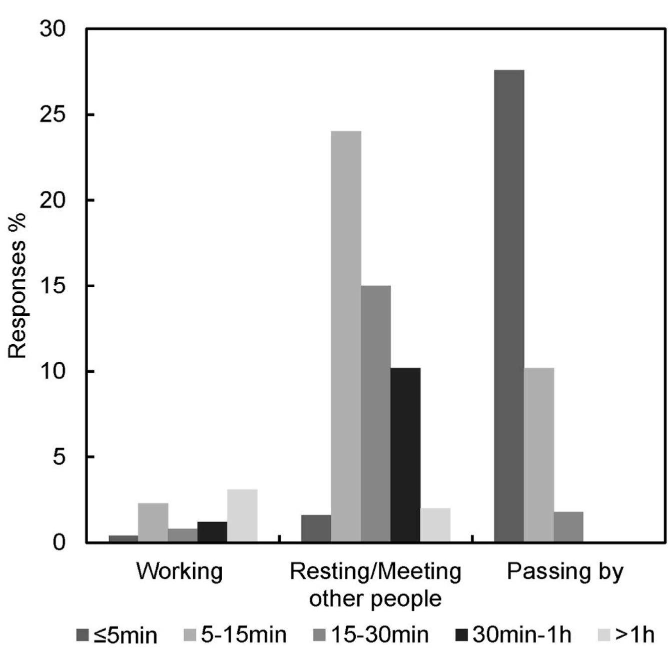


Fig. 9. Frequencies of the exposure time by the responders' purpose of visit.

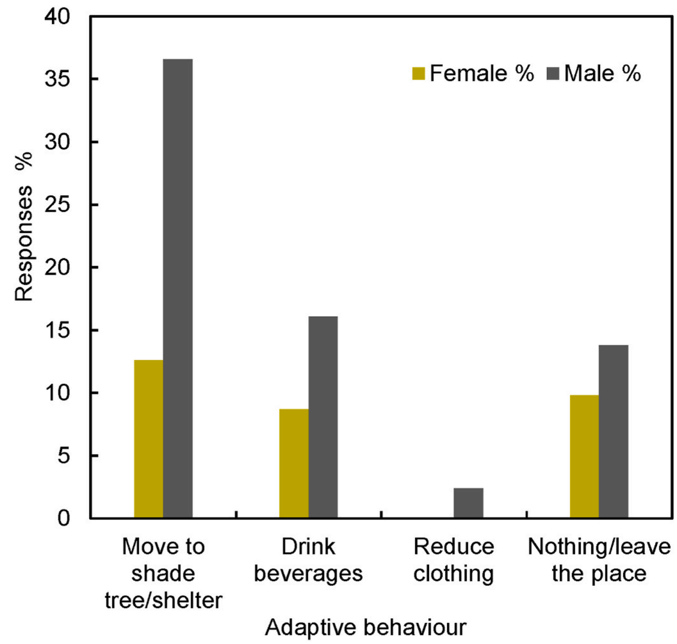


Fig. 10. Frequencies of the responders' gender by the adaptive behaviour.

adjustment represents an instant and remedial action to reduce human thermal discomfort, including all the modifications (personnel, environmental or cultural amendments) a person can make [87].

3.5. Thermal comfort in Constantine

3.5.1. Neutral temperature and comfort range

To perform a linear regression between the subjective (TSV) derived from the survey and the comfort index (PET), it is first necessary to divide PET values into different bins with a 1 °C increment. Then calculate each bin's mean thermal sensation votes (MTSV) [88]. Fig. 11 illustrates the scatter plot of MTSV versus PET, and the correlation equation is expressed as:

$$MTSV = 0.1211PET - 2.7472. \ (R^2 = 0.8997) \tag{3}$$

Linear regression revealed a strong relationship between MTSV and PET with a coefficient of determination of ($R^2 = 0.8997$), indicating that pedestrians' thermal perception was in accordance with the computed thermal comfort. Firstly, the outdoor thermal neutrality was obtained by

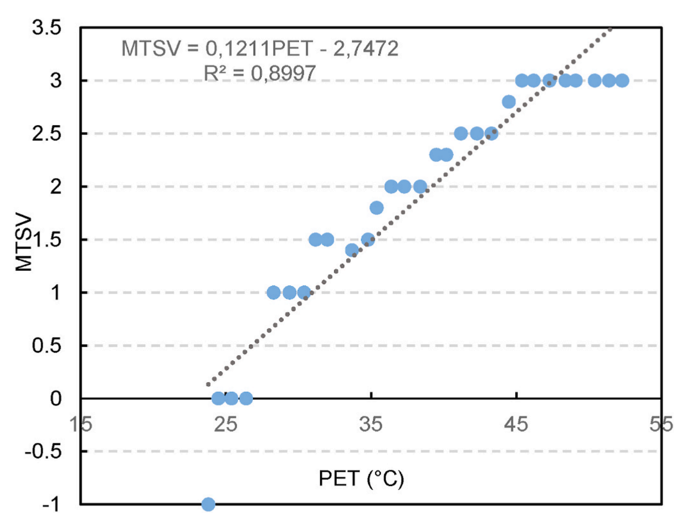


Fig. 11. Scatterplot of the PET versus the MTSV

substituting the mean thermal sensation vote by zero in equation (3); the neutral PET in this study was 22.7 °C. Whereas, the thermo-neutral PET in hot arid climates tends to be higher than 22 °C for example, 26.4 °C in Isfahan, Iran [89]; 28.6 °C in Tempe, USA [86]; and 29.5 °C in Cairo, Egypt [90]. While in moderate climates, the neutral PET was 13.3 °C in Glasgow, UK [91]. Secondly, assuming that the range of ±0.5 on the ASHRAE 7-point scale conforms to the thermal comfort range [58], it was estimated between 18.6 °C ≤ PET≤ 26.8 °C in Constantine during summertime. These results align generally with the comfort zone identified in the hot Mediterranean climate studies as outlined in Table 8. For instance, it was 21.1–29.2 °C in Rome, Italy [92]; 20–25 °C in Crete, Greece [93]; 20–25 °C in Tel Aviv, Israel [94]; and 20–26 °C in Annaba, Algeria [95]. However, a comparison with a similar study [96] conducted in Konya, a Turkish city characterised by a semi-arid climate, revealed that both lower and upper thresholds of the PET comfort range 21.6–32 °C were higher than those obtained in this study, likely due to the acclimatisation phenomenon influenced by geographical location.

As explained by Chen et al. [88], to calibrate the scale of the thermal comfort indices using the subjective thermal perception, two methods are usually employed the linear regression and the probit analysis. In this study, the linear regression method was used to modify thresholds of the PET index, since the thermal sensation categories reported in the survey ranged from ‘Slightly cool’ to ‘Hot’ only few grades of thermal stress were determined. Table 9 present the partial calibration of thermal stress grades acquired through the linear regression equation mentioned above. As can be seen from Fig. 12, it is evident that the width of the PET calibrated grades are larger than the PET original grades developed for middle/west Europe [97]. Therefore, the thermal sensation categories for the warm side were higher than the original ones indicating that pedestrians in a semi-arid climate accept higher temperatures and have more tolerance for the hottest weather due to physiological and psychological adaptation.

3.5.2. Outdoor thermal comfort mapping

The generated outputs from the ENVI-met software aims to obtain detailed, high-resolution maps of the PET index for the selected study sites. The study computed the PET values at different times, including early morning, midday, and noon, as illustrated in Fig. 13. The multiple-time points provide a comprehensive understanding of the diurnal variation in PET values across the studied locations. The interpretation of the maps was based on the calibrated PET defined in the preceding section.

Table 8
Comparison of PET comfort range between different climates.

Studies	Koppen-Geiger climate type	Season	PET comfort range (°C)
Constantine (Present study)	BSk	Summer	18.6–26.8
Isfahan [89]	Bwk	Summer	23–29.7
Tempe [86]	BWh	All seasons	19.1–38.1
Cairo [90]	BWh	Summer/ Winter	24.5–34.5
Glasgow [91]	Cfb	Winter/ Summer	9–18
Dar es Salaam [98]	Aw	Summer/ Winter	23–31
Rome [92]	Csa	All seasons	21.1–29.2
Crete [93]	Csa	Summer/ Winter	20–25
Tel Aviv [94]	Csa	Summer/ Winter	20–25
Annaba [95]	Csa	Summer	20–26
Konya [96]	BSk	Summer	21.6–32

Significance of the symbols in the Koppen-Geiger climate classification: (i) main climates: B–Arid, C–Warm temperate, A–; (ii) precipitation: S–Steppe, w–Winter dry, W–Desert, s–summer dry, f–fully humid; (iii) temperature: k–cold arid, h–hot arid, a–hot summer [54].

Table 9
Partial modification of PET grades by linear regression method.

Thermal sensations (MTSV)	PET (°C)	Thermal stress grades
Very hot	>51.6	Extreme heat stress
Hot (2.5 to 3.5)	43.2–51.6	Strong heat stress
Warm (1.5 to 2.5)	35–43.2	Moderate heat stress
Slightly warm (+0.5 to 1.5)	26.8–35	Slight heat stress
Neutral (-0.5 to +0.5)	18.6–26.8	No thermal stress
Slightly cool (-0.5 to -1.5)	10.3–18.6	Slight cold stress

At 7 a.m., the PET map indicated that over 75 % of the surface area of *Si el Haoues* place (C1) was undergoing ‘No thermal stress’, with PET values ranging from 21 to 26.7 °C. This is attributed to the urban configuration of the space, which provided shade during this hour of the day. However, the remaining surface area that was exposed to direct sunlight recorded ‘Slight heat stress’, with PET values exceeding 26.8 °C. In contrast, the PET values for *La Bréche* Esplanade (C2), and *Hadj Ahmed Bey* place (C3), were found to be comparable. The observed grades of thermal stress varied from 19 to 26.2 °C representing ‘No thermal stress’, which coincides with shaded areas by the surrounding buildings or the presence of trees.

According to the PET map (Fig. 13b), the midday hours, which correspond to the peak diurnal temperature, showed a state of ‘Strong heat stress’ across all the surface areas of the aforementioned sites, with PET values ranging from 44 to 52 °C, due to the prolonged exposure to intensive sunlight. Notably, the mean air temperature (Tmrt) peaked at 65 °C in (C1) at 1 p.m., 79.2 °C at 3 p.m. in (C2), and 66.1 °C at 2 p.m. in the last site (C3), corresponding to the highest values at this outdoor locations (consider Table 6).

At noon (see Fig. 13c), the PET values in *Si el Haoues* place (C1) varied from 35.7–41.9 °C to 41.9–48.1 °C indicating a grade of ‘Moderate heat stress’ and ‘Strong heat stress’, because of the heat accumulation during the morning hours. ‘Slight heat stress’ and ‘Moderate heat stress’ was detected at *Hadj Ahmed Bey* place (C3) covering a PET temperature of 31–35 and 35.4–41.2 °C. While the lowest records of the PET values 29–30.8 °C was observed over *La Bréche* Esplanade. Due to the convective cooling effect induced by the increase of air speed over this open space, resulting in a lower perceived temperature and more cooling sensation [99].

3.6. Post-COVID-19 pandemic effects

Most visitors (67.7 %) of the three outdoor spaces were healthy with no chronicle diseases. Even though in summer 2021, 59.4 % of the participants said, they had already COVID-19, see Fig. 14. Over half (54.7 %) of those surveyed reported that curfew time and social restrictions caused a change in how often they visited the studied sites. Moreover, 56.7 % of respondents stated that physical distancing during the post-pandemic period affected their planned activities, about 40 % of the participants who were out resting and meeting other people said they were influenced by the imposed measures (refer to Fig. 15). However, people who were passing by 28 % said that social distancing did not influence them, as they stayed in general less than 5 min (Fig. 15). Then, the majority of the participants (84 %) contemplated that wearing a face mask outdoors decreased their thermal comfort, just 16 % of face mask wearers felt thermally comfortable (Fig. 14). As explained by Ref. [100] wearing a protective mask at a low to moderate workload impacted human thermoregulation and consequently the heart rate, core temperature and thermal sensation were slightly elevated.

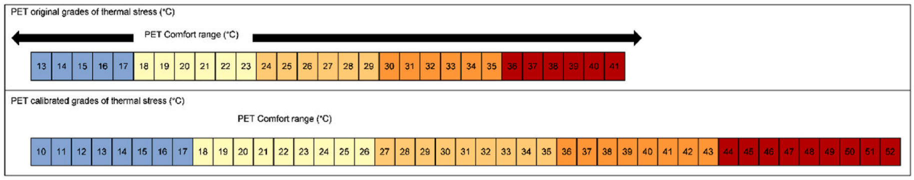


Fig. 12. Comparison between the calibrated and the original grades of PET thermal stress.

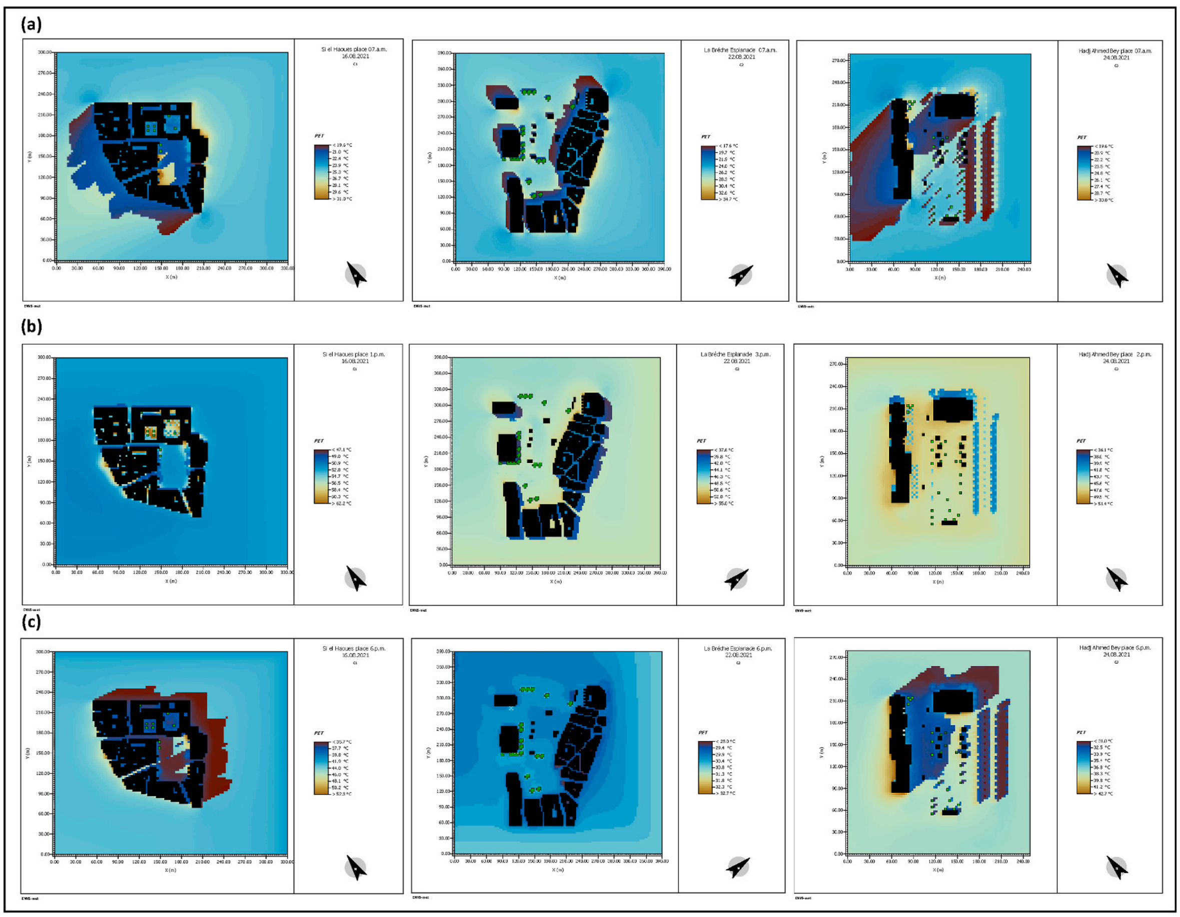


Fig. 13. Simulation results, PET mapping for different times of the day: morning (a), midday (b), and noon (c).

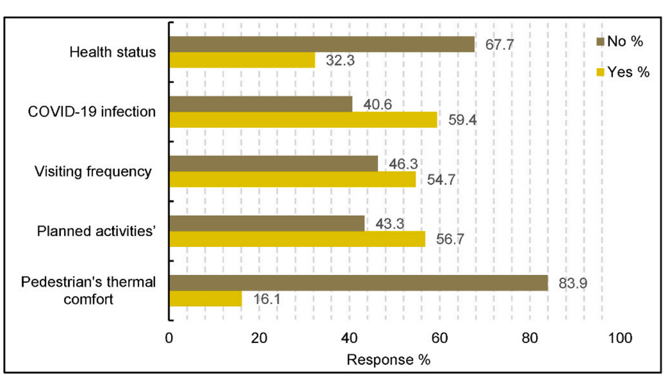


Fig. 14. Quantifying the effects of the COVID-19 measures (curfew, social distancing, facemask).

Additionally, a Chi-Square test has been used to verify whether there is a statistically significant difference in the proportions of the responses. Accordingly, two hypotheses had been proposed: the null hypothesis assumed that the proportions are identical (if the p-value> 0.05), and the alternative hypothesis suggested that the proportions are different (if the p-value <0.05). From the results listed in Table 10, the proportions of responses are significantly different with a chi-square value of X2 = 4,551 (p-value = 0.033) for the planned activities and X2 = 116,472 (p-value <0.05) for the pedestrians' thermal comfort. Contrary to the visiting frequency where X2 = 2,268 (p-value = 0.132) indicating that the difference is not statistically significant and the pedestrians visiting frequency was not associated with the pandemic effects. Overall, the COVID-19 pandemic affected two variables; and it has a highly probable influence on the pedestrian's thermal comfort, and the usage of the outdoor public spaces. In this context, a recent study [101] conducted a series of experiments on the effect of the surgical masks on outdoor thermal comfort including 42 subjects in different seasons. The findings highlighted that, in a warm environment, the use of face masks reduce the thermal comfort of the subjects, and that discomfort was worse for subjects who were walking than sitting. Besides, the discomfort associated with wearing a mask increased when the weather becomes hotter, affecting the face considerably and the chest parts.

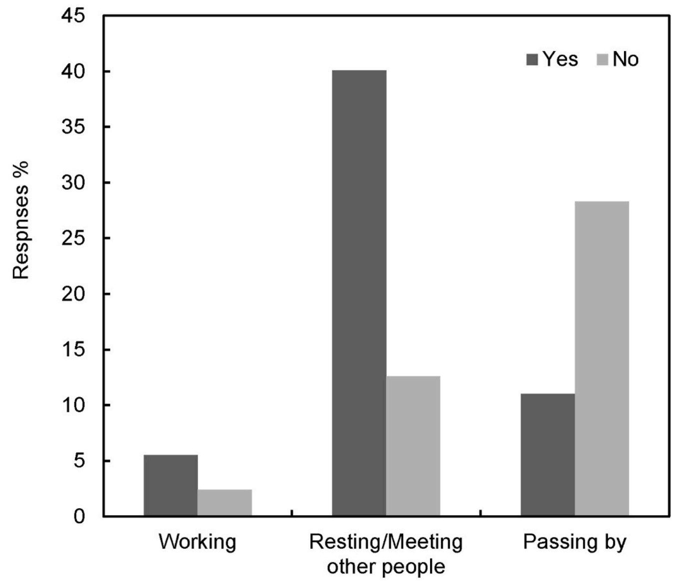


Fig. 15. Cross-tabulation analysis of the planned activities adjustments.

Table 10
Chi-square test results.

	Visiting frequency	Planned activities	Pedestrian's thermal comfort
Chi-Square	2,268[a]	4,551[a]	116,472[a]
df	1	1	1
Asymp. Sig.	0.132	0.033	0.000

[a] 0 cells (0.0 %) have expected frequencies less than 5. The minimum expected cell frequency is 127.0.

4. Conclusion

This paper aimed to assess outdoor thermal perception through a case study conducted in a semi-arid climate region, and addressed the effects of environmental and non-environmental variables on human thermal sensations. Analysing the results from the triangulation of approaches such as field measurements, questionnaire survey and numerical simulations; leads to conclude that:

Summer conditions in Constantine where air temperature can reach 42 °C in outdoor public spaces are less pleasant for pedestrians. The sensation of hot was predominant with 47.2 % votes; the majority of the interviewees (77.5 %) were dissatisfied with their thermal environment. In fact, when the average measured air temperature (Ta) increased at the studied sites; the interviewees expressed more thermal discomfort (TSV> 0). This association was confirmed by a multiple regression analysis, where air temperature was found to be the most significant parameter that influenced pedestrians' thermal sensation.

Moreover, the results of the subjective thermal assessment were in agreement with the assessment scale of the physiological equivalent temperature (PET), the level of 'Very strong heat stress' was detected at the surveyed sites. Also, a strong correlation ($R^2 = 0.89$) between mean thermal sensation votes (MTSV) and physiological equivalent temperature (PET) was found. The binned method between MTSV and PET allowed defining a neutral PET of 22.7 °C and the comfort range of pedestrians was estimated between 18.6 °C and 26.8 °C (PET) in the hot season.

An attempt to assess the thermal adaptation and the behavioural adjustments using The Kruskal-Wallis *H* test, revealed that interviewees' exposure time and the preceding activities had no significant effect on their thermal sensations. In contrary, the short-term thermal history and the purpose of the visit had an influence. And in terms of adaptive behavior, 'move to shade' was the preferred measure for both males and females to decrease their thermal discomfort. Henceforth, planning and managing urban spaces should meet peoples' needs; also, enhancing outdoor thermal comfort in warm environment by providing more shade could reduce considerably human thermal dissatisfaction.

Furthermore, particular attention was given to the effects of COVID-19 restrictions on outdoor activities and human thermal comfort during the post-pandemic period. The findings demonstrated that social distancing protocols influenced planned activities, and the use of face masks decreased the thermal comfort of the subjects. However, the frequency of pedestrian visits to the studied sites was not affected by the post-pandemic enforced measures. Overall, the mobility restrictions and the prevention protocols have revealed the importance of accessible and adaptable outdoor environments. Hence, to address not only the pandemic-induced challenges but also potential future crises, local city policies and regulations on urban planning need to re-examine the design of outdoor public spaces in order to prioritize flexible zoning, enhance sanitation facilities, and promote open recreational areas.

CRediT authorship contribution statement

Afef Ouis: Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Writing – original draft, Writing – review & editing. **Nassira Benhassine:** Validation, Supervision. **Fatih Canan:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Questionnaire survey

Questionnaire survey (Summer 2021)

Place: .... Date: ....Time: ....No:

Section one

1-The questionnaire is accomplished:
☐ Under the shade ☐ Exposed to sun ☐ Cloudy weather

2- Place of residence:
☐ Local ☐ Not local ☐ Abroad

3- Gender: ☐ Male ☐ Female

4- Age: ☐ ≤ 20 ☐ 21-35 ☐ 36-45 ☐ 46-55 ☐ 56-65 ☐ > 65

5- Height: ☐ ≤1.60 ☐ 161-1.70 ☐ 1.71-1.80 ☐ 1.81-1.90 ☐ >1.90

6- Weight: ☐ ≤50 ☐ 51-60 ☐ 61-70 ☐ 71-80 ☐ >80

7- Type of Clothing:

Shirts/Tshirts:	Trousers:	Shoes:	Jacket:	Head:	Other:
☐ Short sleeves	☐ Shorts	☐ Sandals	☐ Sweater	☐ Hat	……………........
☐ Long sleeves	☐ Pants	☐ Shoes	☐ Jacket	☐ Scarf	
☐ Sleeveless	☐ Dress	☐ Boots	☐ Coat	☐ Parasol	

8- Why you are here (Reason to be in this place)?
☐ Working ☐ Resting/Meeting people ☐ Passing by ☐ Shopping

9- How long have you been in this place?
☐ ≤5min ☐ 5-15min ☐ 15-30min ☐ 30-1h ☐ >1h

10- Where have you been in the last (15min-30min) before visiting this place?
☐ Outdoor in the sun ☐ Outdoor in the shade ☐ Indoor with AC ☐ Indoor without AC

11- What activity have you done in the last (15min-30min)?
☐ Seating ☐ Standing relaxed ☐ Walking ☐ Other…………….

12- What measure would you take if you feel too hot in this place?
☐ Move to shade ☐ Drink beverages ☐ Reduce clothing ☐ Nothing/leave the place

Section two

1- How do you feel in this place (currently)?
☐ Cold ☐ Cool ☐ Slightly cool ☐ Neutral ☐ Slightly warm ☐ Warm ☐ Hot

2- Would you rate your thermal satisfaction please?
☐ Very satisfied ☐ Satisfied ☐ Slightly satisfied ☐ Neutral ☐ Slightly dissatisfied ☐ Dissatisfied ☐ Very Dissatisfied

Section three

1- Do you have any health problems or chronicle diseases?
☐ Yes ☐ No

2- Were you infected by the COVID-19?
☐ Yes ☐ No

3- Did curfew time affected your usage and attendance in this place?
☐ Yes ☐ No

4- Did social distancing influence your planned activities in this place?
☐ Yes ☐ No

5- Do you feel thermally comfortable wearing face mask in this place?
☐ Yes ☐ No

Fig. S1. Questionnaire survey used to collect data during the survey days.

Appendix B. Multiple regression analysis

Table B.1
Multiple linear regression results between microclimate variables and thermal sensation votes

R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change	Durbin- Watson
0.863[a]	0.744	0.740	0.515	0.744	180.953	4	249	0.000	1.552

[a]. Predictors: Ta, Tmrt, Rh, Va.

Table B.2
Partial significance (Coefficients table) of the variables (Ta, Tmrt, Rh, Va)

Model	Coefficients		*t*	P-value	VIF
	B	Std. error			
Constant	−4.946	0.560	−8.830	0.000	–
Air temperature (Ta)	0.153	0.015	10.004	0.000	5.030
Mean radiant temperature (Tmrt)	0.027	0.005	5.690	0.000	3.503
Relative humidity (Rh)	0.012	0.005	2.706	0.007	3.502
Air velocity (Va)	0.143	0.039	3.685	0.000	1.419

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