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Title

Thermal comfort improvement in urban spaces with water spray systems: Field measurements and survey

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Abstract

An experimental study was conducted to improve the comfort and liveability of urban open spaces during the hottest months of the summer by implementing an overhead water mist cooling system. The campaign was conducted in two different Italian urbanscapes (Ancona and Rome, representative of Cfa and Csa climates) one after the other.

Monitoring data and comfort questionnaires were combined to extract useful information by means of statistical tests, regressions and data mining algorithms and, ultimately, to delineate design and operating guidelines to maximize people's satisfaction with the misted environment.

The cloud of droplets reduced the temperature and the UTCI by 8.2°C and 7.9°C respectively, against a 7% mean humidity premium. The vertical cooling and humidification profiles obeyed a Lorentzian distribution, peaking within approximately 0.5m of the injection. The severe overheating experienced outside of the cooled areas evanished under the spray, with 67% (Ancona) to 90.6% (Rome) of respondents reporting only slight bending from thermal neutrality. Perception and preferences towards solar radiation, humidity level and wind all improved within the droplets mist.

In terms of comfort-oriented, optimized design criteria, the system proved to work best with a dominant and steady light breeze (1-2 m/s), in highly irradiated sites and suspended at 1.2-1.5m above the average height of users.

Keywords

Climate mitigation; Urban Heat Island; evaporative cooling; water spraying; comfort questionnaires; outdoor environmental quality.

1. Introduction

Hazardous and thermally stressful climate events have increased considerably worldwide in recent years, not only occasionally but also as a mean trend, thus putting a strain on 1) the energy used for cooling, 2) public health (also by increasing the burden of air pollution), 3) the ability to work and productivity, 4) the usability of public spaces and social prosperity. Startlingly, 30% of the world's population is already exposed to deadly climatic conditions for at least 20 days a year [1], with up to 8,628 annual temperature-driven deaths envisioned by 2100 in a no-action scenario [2].

Heat is one of the main climate threats specifically relevant to cities [3]. The temperature rise in dense urban areas is moving at a faster pace than in their rural surroundings [4], owing to different materials, wind patterns, atmospheric aerosol pollution and natural/anthropogenic heat emitters. Dubbed the Urban Heat Island (UHI) effect, this phenomenon is escalating fast. Increased ambient temperatures magnify the penetration and usage of air conditioning [5–7], while degrading the efficiency of thermal machines and urban PV. The overall environmental cost of this vicious loop is phenomenal, when we consider that, although carbon dioxide is the most publicized contributor to global warming, HCFCs (Hydrofluorocarbons included in refrigerants used in cooling devices) have a global warming potential (GWP) 3000 times that of an equivalent volume of carbon dioxide [8]. Averting the abuse and misuse of cooling systems is a matter of public awareness and utilization patterns, but overheating mitigation is a necessary precondition.

Several UHI counteractions might be conceptualized (combining cool materials, water systems, green cover and solar shadings) to soften peak urban temperatures by a maximum of 2.5°C or thereabouts [9]. But extensive mitigation/adaptation actions tend to be costly and time-consuming: the accuracy and sophistication of preliminary on-site diagnostics (to spot UHI and conceive proper mitigation scenarios [10–12]) and the degree of urban remodelling required, generally hinder any bold counteractions. Consequently, few broad actions are reported to date [13].

Yet, if we focus on the point scale, water-based technologies attain the most significant local temperature reduction through a process of evaporative cooling [9]. Among them, mist spraying can be particularly efficient, since the cooling medium is close to individuals benefiting from it. Reportedly, the temperature drop could be by 7-10°C on an over-30°C day, with quite good correspondence between experimental and numerical studies [14,15]. For instance, in our previous experimentation on mist spraying [16], we measured maximum cooling of 7.5°C on the hottest day of the monitoring campaign (33°C, 54% humidity). In [17] the authors observed the cooling impact of dry-mist systems by simulating different environmental conditions in a climatic chamber. They measured temperature drops of up to 7.5°C, when the wet bulb depression was 8.96°C, with a +47.2% humidity premium. Huang et al. [18] monitored high-pressure spray cooling in an open outdoor waiting area of the World Expo in Shanghai, 2010: when the untreated outdoor areas stayed at 34-

40°C in the 32-55% humidity range, the measured drop was 6-12°C within 1m of the spray column, 1.5-4°C within 3m, 0.5-1.5°C within 7m. Likewise, in [19], Dominguez et al. monitored the intermittent operation of 128 micronizers installed under pergolas during the Seville Expo ’92. At a 42°C ambient temperature, the local reduction was by nearly 10°C, keeping humidity below 65%. At another Expo (Aichi, Japan 2005), fine mists sprayed outdoors from overhead nozzles caused temperature reductions of up to 2-3°C at pedestrian height [20]. In [21], Atieh and Al Shariff demonstrated that solar-powered misting systems could cool the air by 10°C in a sub-tropical desert climate, with a maximum humidity gain of about 25%. Wind also plays a role, as corroborated in [22], where a fine water mist was experimentally and numerically investigated in an outdoor open environment, subject to variable wind patterns. The measured temperature drop reached 6.7°C, while numerical simulation suggested a reduction of more than 10°C in downwind conditions. In a large atrium, Farnham et al. [23] experimentally tweaked the height of a single misting nozzle to determine the no-wetting altitude. In this context, the maximum temperature drop was 2.1°C.

In addition to field-collected evidence, numerical analysis confirmed the general trends. Many studies outline that CFD codes better depict the scattering of a fine water mist within a turbulent airflow without the uncertainties caused by sensor wetting [24]. The CFD studies by Montazeri et al. [25–27] are very detailed. In their latest publication [25], they systematically characterized mist cooling by simulating the action of 15 hollow-cone nozzles in a Dutch courtyard under 2006 heatwave conditions. The maximum temperature and UTCI reductions touched 7°C (-2°C up to a distance of 8m) and 5°C at pedestrian height. The CFD model was calibrated on wind-tunnel measurements by Sureshkumar [28], satellite imagery and previous systematic parametric analyses: inlet air temperature, humidity ratio, velocity, water temperature and droplet size distribution were discussed in [27], whereas grid-sensitivity, turbulence modelling and number of injected streams were dealt with in [26].

Versatile in design and control, mist cooling has much potential in urban planning and street landscaping (with the purpose of cooling the ambient air and improving outdoor comfort) at extremely low installation, operation and maintenance cost. Therefore, the risk of triggering social disparity and energy poverty, to the detriment of vulnerable and low-income populations, is minimal. Moreover, water misting systems are uniquely beneficial to outdoor environmental quality, since, in addition to their heat suppression capabilities, they i) consume modest quantities of water, requiring no custom-fit hydraulic plants, ii) are non-toxic, iii) expel dust and other common pollutants from the exposed area [29], iv) omnidirectionally attenuate solar radiation, including the near-ultraviolet quota, responsible for human tissue damage [30], v) repel mosquitos, flies, wasps and other insects, thus offsetting the potential side effects of moistening [31,32]. On top of that, water nebulization is recognized as a valid preventive measure against heat stress and emergency treatment for heat stroke [33].

Against this backdrop, we devised, installed and monitored a customized web of nebulizers in two Italian urban settings (in the city of Ancona first and later in the capital, Rome), different in complexity (to account for diverse UHI levels and triggers), climatic frame (to account for distinct boundary forcers) and typical users (to account for biodiversity).

Given the number of potential interplays at stake, a purely objective assessment of the impacts on the surrounding temperature might have been defective, mostly because of the accentuated environmental variability (in terms of wind speed, rainy events, sky view, ...) and behavioural richness (in terms of exposure time, activity, age, gender, clothing, and so forth) of outdoor spaces [34].

To overcome such uncertainties, a valuable and well-established practice is to combine micrometeorological measurements and transversal field surveys [35–40]. For instance, Uchiyama et al. [41] distributed comfort questionnaires to passersby under the overhead fine mist spray they monitored in a semi-enclosed train platform. People were asked about their comfort and wettedness: 77% claimed increased thermal comfort at a 1-2°C temperature drop with the ambient air at 34°C. Slight and significant wetting was reported by the 53% of respondents in the misted area. Similarly, Ishii et al. [42] tested 30 dry-mist nozzles in a railway space. In the morning (9am - 1pm) cooling was by 1.63°C, hitting 1.90°C at peak hours (1pm – 3pm). 80% of the respondents to the comfort questionnaires were comfortable in the cooled area. Farnham et al. [43] characterized the impacts of natural and forced convective spray cooling by focusing on the physiological effects: the authors performed skin surface temperature and heat flux measurements while handing out comfort questionnaires. 141 people took part in the survey on hot summer days, and reported their ‘thermal sensation’ (on a 9-point scale), ‘overall comfort’ (on a 7-point scale), ‘skin wittedness sensation’ (on a 7-point scale) and ‘wettedness impression’ (3 options). The average thermal sensation changed from +2.7 (hot) to -1.41 (slightly cool) after misting. Wettedness sensation increased, but pleasantly. Finally, Wong and Chong [44] collected personal feedback in Singapore, from people sitting in semi-outdoor dining areas, equipped with misting fans or lines. A 7-point scale was adopted for thermal sensation, overall comfort and humidity sensation, while humidity preference was verified on a 3-option basis. They observed a 1-vote shift towards fresher sensations while under the mist, with no impact on humidity at such low activity levels.

Compared with the above studies, the purpose of this investigation was slightly different: we aimed to compare the level of comfort within and outside the nebulized area to i) spot opportunities for design refinement (height, density of nozzles …), ii) identify the most appropriate end-user category (age group, gender, size, activity level …) and iii) gain insight into the multifarious ways water mist alters sensations and preferences towards individual environmental factors (temperature, humidity, sun, wind). The ultimate goal was to define the optimal configuration for a powerful and effortlessly implementable tool against urban overheating.

In the following paragraphs, the methodology and outputs of the experimental test are described in detail.

2. Experimental setup

The monitoring took place over 4 to 6 summer days in each location. The climatic profiles are reported in Appendix A.

Both the sensor network and the comfort survey were conceptualized to gather data and information to characterize water nebulization as an OEQ system rather than just a cooling device.

2.1 Test rig

The prototype consisted of 24, 1-m-spaced, hollow-cone nozzles arranged in 4 parallel strings. With a 0.20mm orifice and a 70 bar pressure, the droplet diameter distribution was centred below 10μm (as per manufacturer's instructions). The fully suspended structure comprised support brackets, tensioners, springs, and pulleys, easily adaptable to each location. The high-pressure, self-compensating pump withdrew modest flow rates (1.5l/min) from local fountains, without interrupting the supply of potable water. Thus, water consumption over a 10-hour duty cycle (10am to 8pm) was $0.9m^3$/day. The pump absorbed $919W_e$ and was controlled via a Virtual Instrument (VI) platformed in LabVIEW: in this way, the pressurized flow could be operated manually or automatically.

The sensor network consisted of a meteorological station, used to characterize the undisturbed location (reference to quantify cooling and humidification), a suite of miniaturized thermohygrometers to map temperature and relative humidity beneath the spray and a globe thermometer to record the mean radiant temperature within the mist.

The LSI Lastem meteorological station featured three probes:

- Thermohygrometer DMA 572.1 (Pt 100 + capacitive hygrometer), measuring in the ranges -30-70°C (with an accuracy of ±0.2°C) and 0-100% (accuracy of 1.5% in the 5-95% interval) with a response time of 10s.
- Tacogonioanemometer DNA 022 (cup type), measuring in the ranges 0-60m/s (accuracy of 1.5%, time constant of 2.5s) and 0-360° (accuracy of 1.5%, time constant of 0.74s).
- Global radiometer DPA 153 (first class pyranometer) measuring in the 285-2800nm spectral range from 0 up to 2000 W/m^2 (uncertainty <5%, response time <30s).

Five PCMINI52 thermohygrometers by Michell Instruments mapped the cooled area, being highly responsive (<10s for 90% step change). They were sun-shielded and customized in-house with a protective HDPE cover, specifically to avoid wetting the sensor and thus overestimation of the cooling potential. The accuracy was ±0.2°C for temperature and <±2% for relative humidity. The five probes were distributed at the centre of the spraying rack and at the midpoints of its perimeter. The height was set to 1.1m according to comfort Standards [45] (suggested height for breast level of a standing person and for head level of a sitting person).

A Ø150mm, Pt100 globe thermometer (accurate to ±0.2°C) was located close to the central thermohygrometer to keep track of the evolution in terms of mean radiant temperature, too.

Finally, a KEMO M152 rain gauge was incorporated to stop any injections in the presence of raindrops.

The outputs were recorded every 10s and averaged over 1-minute within the same VI used to pilot the pump.

Furthermore, during the monitoring campaign in Rome, on the 30 August, 4 additional thermohygrometers were mounted on a 3m high tripod to keep track of the vertical profiles. The ATMOS 14 probes were accurate to 0.3°C and ±2% for temperature and relative humidity, respectively. The assembly was located between the third and the fourth nozzle of the central row to record the temporal evolution at 1.1m, 1.7m, 2.1m and 2.5m above the ground, with a 1-minute time step.

The setup is shown in Fig.1 in both configurations (Ancona and Rome). See [16] for a CAD representation of the sensor network and more detailed information.

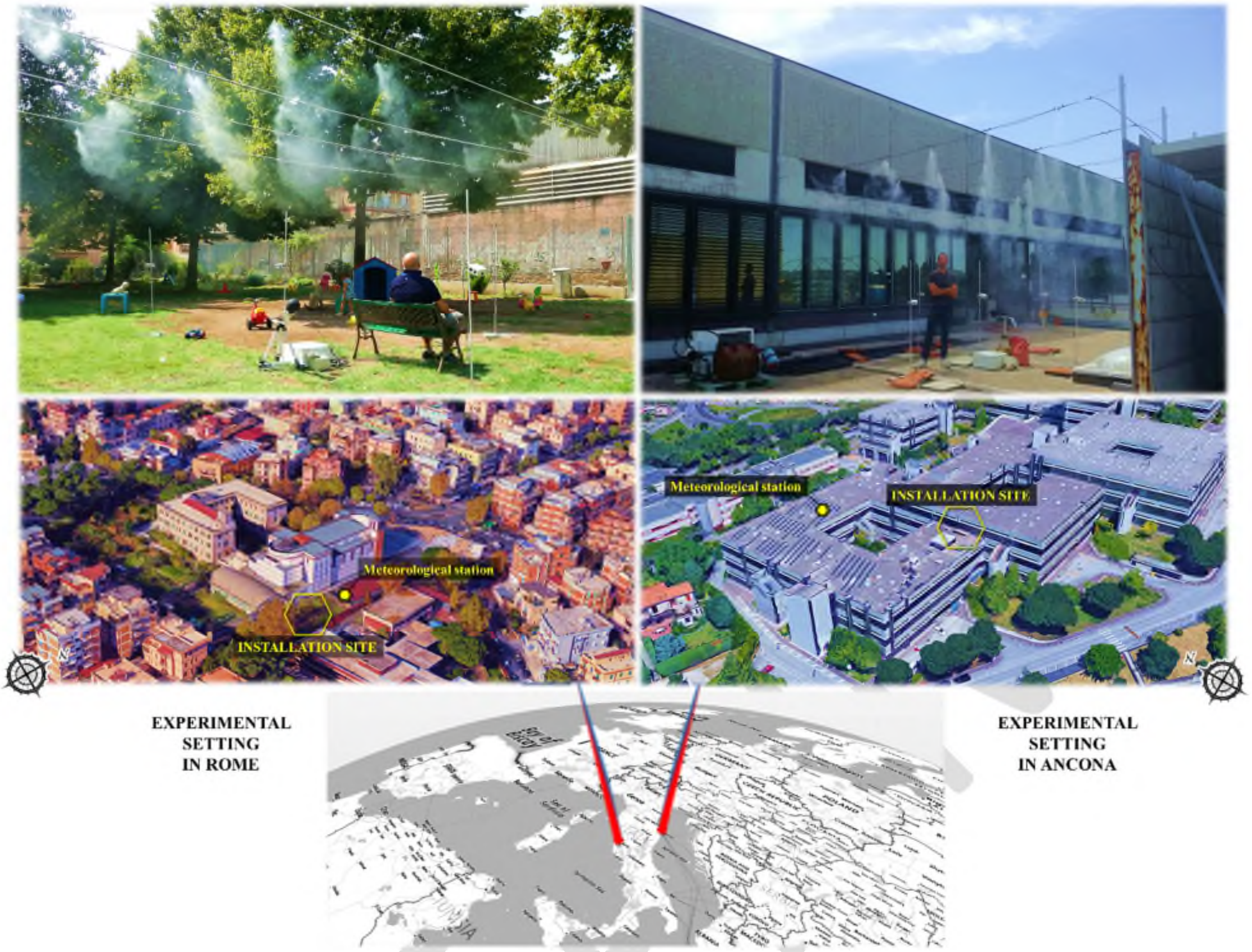


Fig. 1. Geolocalization of the monitoring settings and corresponding experimental rigs.

2.2 Test locations

Table 1 summarizes the main information on the two experimental settings. The geographic coordinates are provided together with the climate classification according to Köppen and Geiger [46].

As a coastal city, Ancona typically features mild and temperate Mediterranean climatic conditions. Moisture and precipitation stay high all year round, with monthly averages of over 70% and 50mm, respectively. Ancona was thus selected to check water spray efficacy in the presence of high atmospheric humidity.

Conversely, Rome suffers from continentality and an intense urban heat island effect, with summer UHI of up to 2.8°C [47]. The climate in summer is relentlessly hot, often with little or no breeze.

The timing was scheduled by looking at the monthly average values for maximum and minimum temperature, relative humidity, rainfall and absolute heliophany (number of hours of direct solar radiation with no cloud cloaking) reported at the bottom of Table 1 (averages over a 30-year period, from 1961 to 1990 [48]). The campaign took place over the warmest months of summer: for equal monthly mean temperature, the most humid months were selected. Thus, the first run was conducted in late July in Ancona and the second in August in Rome.

Table 1 reports the average conditions during the survey, namely:

- air temperature (Ta_avg), humidity (RH_avg), wind speed and direction (ws_avg, wd_avg) and horizontal global irradiation (Ioh_avg), returned by the meteorological station;
- the average offset between the minimum temperature beneath the spray and thermal neutrality (Dtn_avg). The comfort temperature was set to 27.2°C as suggested in [36];
- the mean radiant temperature, computed by post-processing the globe-thermometer output according to ISO 7726 equations [45].

Table 1

Monitoring campaigns: climatic characterization (Ta=air temperature, RH=relative humidity, ws=wind speed, wd=wind direction, Ioh=global horizontal irradiation, Tmr=mean radiant temperature, _avg=average)

Observation period	City	Latitude		Longitude	Altitude [m a.s.l.]	Köppen-Geiger climate	
16th-19th July 2018	Ancona	43°35'13.3"N		13°30'54.0"E	102	Cfa	
	Ta_avg [°C]	RH_avg [%]	ws_avg [m/s]	wd_avg [°]	Dtn_avg [°C]	Ioh_avg [W/m^2]	Tmr_avg [°C]
	30.9	44.9	2	197.2	2	558	51.5
Observation period	**City**	**Latitude**		**Longitude**	**Altitude [m a.s.l.]**	**Köppen-Geiger climate**	
23th-30th August 2018	Rome	41°52'34.7"N		12°33'59.6"E	44.5	Csa	
	Ta_avg [°C]	RH_avg [%]	ws_avg [m/s]	wd_avg [°]	Dtn_avg [°C]	Ioh_avg [W/m^2]	Tmr_avg [°C]
	29	50.2	0.7	159.9	1.8	394.2	41.6

Month	T_{max} [°C]		T_{min} [°C]		RH [%]		Rainfall [mm]		Absolute Heliophany [h]	
	ANCONA	ROME	ANCONA	ROME	ANCONA	ROME	ANCONA	ROME	ANCONA	ROME
January	9	11	1	4	82	67	51	25	3	4
February	10	13	2	5	81	65	53	21	3	5
March	13	15	4	7	76	62	68	22	5	5
April	17	19	7	9	75	60	54	21	6	6
May	22	23	11	13	74	55	60	16	8	8
June	25	27	14	17	71	54	55	11	9	9
July	28	30	16	19	70	49	52	5	10	11
August	28	30	17	19	70	52	84	8	10	10
September	24	27	14	17	75	59	73	21	8	8
October	20	21	10	13	79	64	72	36	5	6
November	14	16	6	8	83	68	80	35	3	4
December	10	12	2	5	82	68	74	29	2	3

In Ancona, the spray system was installed on the west-oriented terrace of the Faculty of Engineering (UNIVPM) about 160m above sea level. The system stretched about 7.5m from a cement wall to the external glazed wall of the university offices (Fig.1), suspended 3.3m above the ground. The meteorological station was placed 50m away, on the same terrace.

The university stands on the top of a hill, therefore solar radiation and wind reached the experimental rig largely unimpeded. This setting was thus representative of a sunny and windy location, principally serving young people in the 19-30 age range.

In Rome, the experiment took place in a 50m by16m green park located in a peripheral district about 7km from the city centre. A line of trees provided solar shading throughout the area from nearly 4:30pm onwards. Low wind speeds were dominant. The water system was rearranged, between the west-side fence and the east-side line of trees. Borrowing from the precedent test results, the height was reduced to 2.8m. The meteorological station was placed 16m from the cooled perimeter, within the park’s gate for vandalism prevention reasons.

2.3 Comfort questionnaires

Feedback was collected by means of comfort questionnaires. Compliance with ISO 10551 [49] was observed to ensure plain and simple communication and room for comparative assessments. Specifically, the questionnaire included four main sections (see Appendix B).

The first was about personal information: in addition to gender and age, special attention was given to:

- Activity: ASHRAE Standard 55-2004 [50] suggests a time-weighted averaged metabolic rate (M) when individuals are likely to change their occupation over a period of one hour or less as in outdoor spaces. Therefore, people were asked to state their activity at the time of completing the questionnaire and half an hour earlier. The corresponding weights were set to 0.7 and 0.3 as in [36], according to the Bouden and Ghrab method [51].
- Clothing insulation $\mathrm{I_{CL}}$: ASHRAE Standard 55-2004 [50] method 3 was applied so that the thermal insulation of the outfit could be estimated by summing up each selected garment per body part (Table A.1, Annex A of ISO 9920 was consulted [52]). Also, the pumping effect on clothing thermal insulation for moving subjects was considered:

  $$\mathrm{I_{CL,moving}} = \mathrm{I_{CL}} \cdot \left(0.6 + \frac{0.4}{\mathrm{M}}\right) \quad 1.2\ \mathrm{met} < \mathrm{M} < 2.0\ \mathrm{met} \qquad (1)$$

  where M is the metabolic rate.
- Pregnancy and unhealthy conditions: as homeothermy slightly bends for expecting mothers, feverish and metabolically-altered individuals, this information was used as an exclusion criterion against potential outliers.
- Height: one particular aspect related to overhead water spray concerns the vertical temperature and humidity gradients. Hence, the potential interrelation between the

respondents’ size and environmental satisfaction was also addressed. The reported height was adjusted if respondents were sitting on the bench beneath the spray (as stated in the activity section) and set to the conventional height of 1.1m for head level [45].

Respondents were asked to note the time they entered and exited the cooled space, so that the answers could be related to the average environmental conditions. When dealing with wind data, given that both magnitude and variability affect human perception, the following equation was applied, as in [35,36,53]:

$$\mathrm{ws}^* = \mathrm{ws}_{\mathrm{max}} + SV \tag{2}$$

where maximum wind speed $\mathrm{ws}_{\mathrm{max}}$ and the standard deviation SV of the relevant measurement set are linearly combined. However, as this formulation tends to overestimate the actual air velocity, turbulence intensity TU (percentage ratio between SV and ws) was computed too.

The second section dealt with thermo-hygrometric comfort. It was structured to check thermal perception, thermal preference and tolerance on subjective judgment scales, regarding both the unmitigated and mitigated environments (thus each question was asked twice). The ASHRAE symmetrical 7-degree 2-pole scale (-3, -2, -1, 0, +1, +2, +3) and the McIntyre symmetrical ternary 2-pole scale (-1, 0, 1) were used as they are well established metrics. The aim was to spot perceptive alterations produced by the water mist in terms of wetness and sultriness, wind force and gusts, solar power and glare. Finally, people were asked to define their overall thermal experience as comfortable, acceptable or uncomfortable, to check whether the feedback for individual environmental parameters converged into a consistent global judgment. Hence, we collected 8 comfort indicators for both the unmitigated (later denoted by “_u”) and the sprayed area (denoted by “_s”): thermal sensation vote (TSV), sensation and preference vote for humidity (HSV and HPV), wind (WSV and WPV), solar radiation (SSV and SPV) and thermal comfort vote (TCV).

The third section was about behavioral patterns: the interviewee was categorized in terms of utilization of the outdoor spaces and level of acclimatization. An outdoor occupancy of at least 15 minutes was adopted as the exclusion criterion for thermal adaptation (minimum recommended by ANSI/ASHRAE Standard 55 [50]).

Finally, an opinion section was appended at the end to collect comments and suggestions.

2.4 Methodology

Monitoring and survey data were harmonized to comparatively characterize the mitigated and unmitigated locations and delineate comfort-optimal design criteria (height of the nozzles, anthropogenic and environmental characteristics of the installation site, time of operation …).

The first step was temporal alignment. The time to finish the questionnaire (3-4 minutes) and the time spent under the spray (5-7 minutes) were matched to the 1-minute average of all measured variables, (including maximum, minimum, standard deviation and derived quantities, if applicable). Secondly, we looked into potential correlations between comfort votes and concomitant personal and environmental variables. We carefully investigated the human samples, the daily patterns and the role of the respondents' height. The non-parametric Spearman correlation test was used to measure the strength and direction of association among thermal response votes, as they are non normally distributed variables. A level of 0.01 was selected to evaluate the significance of the results. Conversely, the non-parametric Kruskal-Wallis H test was applied to evaluate how TSV depended on clothing, met, gender, height, age, frequency and exposure time. A 95 % confidence interval was considered, at a significance level of 0.05.

Finally, we uncovered relationships between seemingly unrelated data by means of association rules. The Frequent Pattern (FP)-Growth Algorithm, proposed by Han in [54], was utilized as the mining method, given its proven performance over other popular methods, e.g. the Apriori Algorithm [55],the TreeProjection [56], Eclat [57] and Relim [58]. We looked for high-confidence causal links (confidence≥0.95) and progressively increased the support from a minimum of 10%. In this way, we mined the entire database, only preserving those association rules - if there were any - that were found to fail less than 5% of the time on items appearing in at least 10% of the set (thus the very dominant ones).

3. Results

In Ancona, most of the interviewees were enrolled students and university staff. The survey took place right before the summer holidays, hence, 211 valid questionnaires were collected over four days (only one was invalidated on account of pregnancy). In Rome, the influx of people was particularly sparse because of typical heat-driven urban voiding. Over one week, 121 questionnaires were handed in (only 4 on the last day of the campaign), out of which 2 were invalidated on account of pregnancy and 3 because they were incomplete. In similar investigations (parks, squares, pedestrian areas, university campuses...), the number of interviewees ranged between 8 and 2700 people [40].

A comprehensive view of the participants is shown in the pie charts in Fig. 2. Moving radially from the centre outwards, the percentages in terms of gender, age range, height, metabolic rate and thermal insulation of garments are displayed for both locations. It is thus possible to spot the main similarities and discrepancies between the two human samples, summarized here:

- in both cases, men outnumbered women: the male-female ratio was fairly balanced in Rome (56% vs 44%), resulting in an unbiased representation of gender differences whereas in Ancona the gap exceeded 20%;
- the age group distribution was heavily different: while, as expected, young people were more numerous at the university site in Ancona (64.5% in the 21-35 range, no one over 65), in Rome, the majority of respondents were parents with babies/toddlers and elders. All the groups were represented including children under 10 (1.6%) and seniors over 80 (4.3%), with the 36-50 group holding the biggest share (34.5%);
- people with heights in the 1.5-1.8m range cumulatively accounted for 60-70% of the samples. In Rome, a considerable percentage fell in the below 1.5m group, only partially due to the participation of children: people moved a bench under the sprayed area to enjoy the coolness so the share of seated people (whose heights were adjusted accordingly) increased. The over 1.85m group was also covered (5%). In Ancona, 20.9% of people were 1.8-1.85m tall, but no one was taller than that or seated (although chairs were made available on that occasion,too);

- activity levels were comparable: in both locations, people were mostly standing still or slowly walking (47% in Ancona and 49% in Rome, between 1.2-1.5met). More sedentary activities (<1.2met) involved another 47% of respondents in Ancona and 30% in Rome. More intense activities did not take place in the first setting, but were performed by about 20% of the Roman interviewees (given the proximity to the local playground);
- in relation to clothing, almost equal percentages of very light garments (sleeveless T-shirts and shorts/short skirts, corresponding to less than 0.3clo) and mid-covering summery garments (0.4-0.5clo) were recorded (54.5% and 25.6% in Ancona vs 54.3% and 25% in Rome). In Rome, seniors and mothers generally wore long trousers and long-sleeve shirts which made the >0.5clo group more populated (8% against 3% in Ancona).

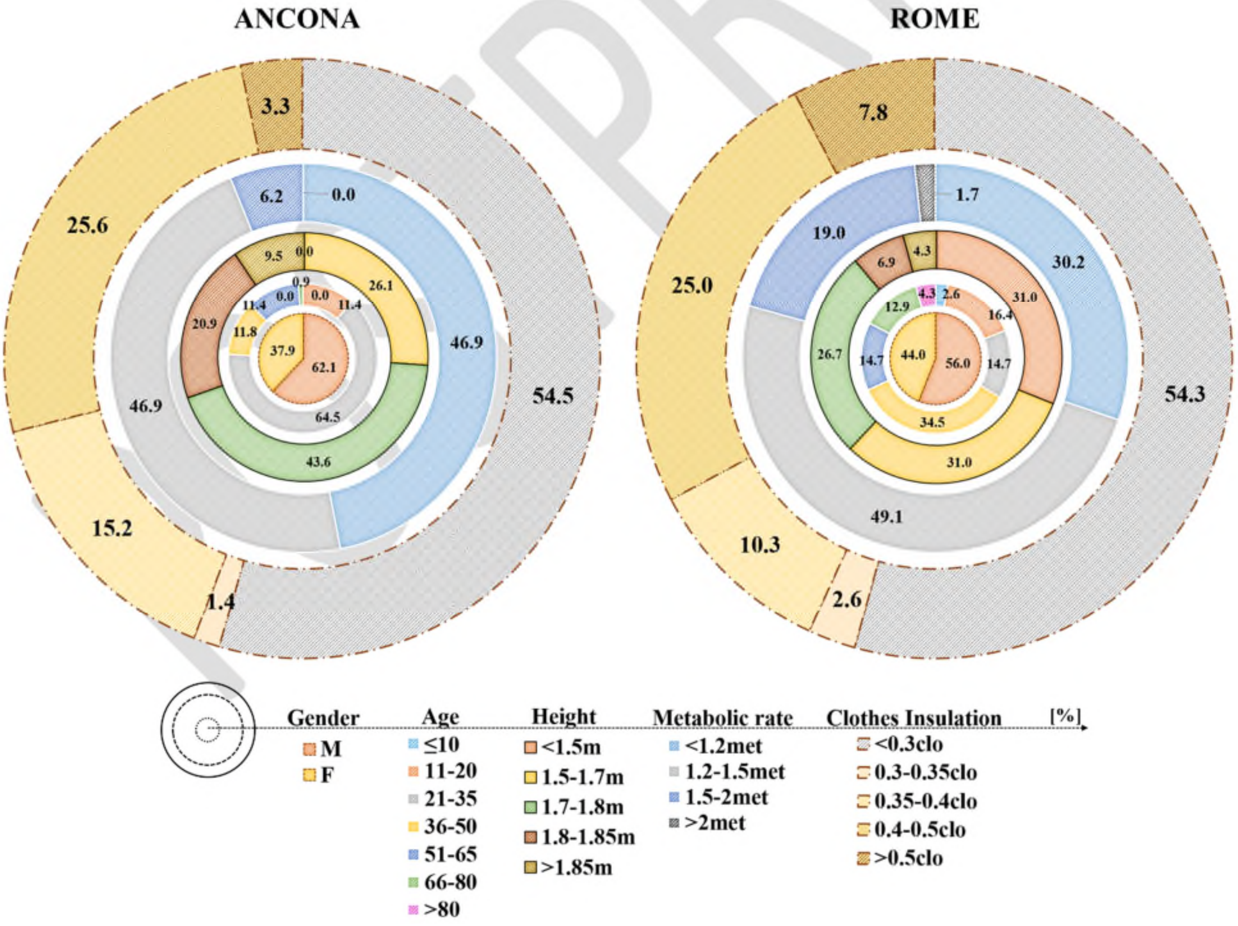


Fig. 2. Demographics and personal variables of the respondents in Ancona (left) and in Rome (right).

In Ancona most questionnaires (about 34%) were handed in after 6pm (right before people left the university), with an almost regular influx of interviewees distributed in the morning, lunchtime and early afternoon. In Rome, people systematically avoided spending peak hours outdoors and the entire area remained almost unoccupied until late afternoon (see Fig. 3).

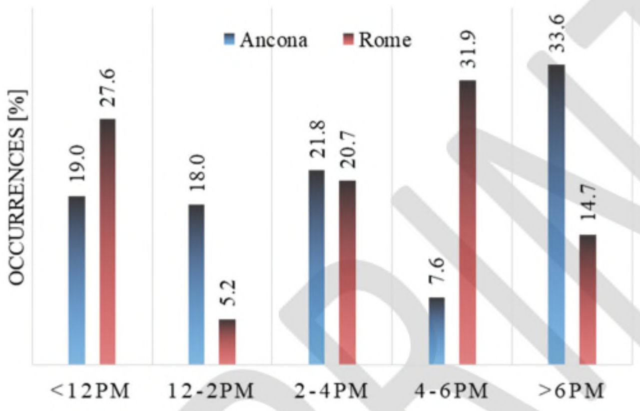


Fig. 3. Percentage feedback at different times of day.

3.1 Main findings and role of time

Fig. 4 and Fig. 5 plot the percentage distribution of all comfort votes in the relevant sub-values (depending on the judgment scale) and different times of the day.

The strongest feedback regarded the comprehensive judgment of the local microclimate (TCVs). Essentially, no one found the cooled area uncomfortable or the non-cooled area comfortable, either in Ancona or Rome. While 63% and 32% of the respondents felt uncomfortably hot with no mitigation, in the two locations, 5% to 0% felt the same within the mist.

In Ancona (Fig. 4), 81% of the answers fell between +2 and +3, while a negligible 3% of people felt thermally neutral with no nebulization in place. Conversely, beneath the spray, 63% voted slightly cool or cool, with another 30% between neutral and slightly warm.

During peak hours (12 - 2pm window), 83% of people felt uncomfortably hot outside of the misted area: the percentage plummeted to 4% as they moved into the cloud of droplets, with nearly 70% of people voting between -1 and +1.

Both humidity sensation and preference were significantly altered by the evaporative processes: 20% of the respondents who noted dry conditions in the unmitigated area had their sensations change entirely to pleasant (rather than humid) when they entered the nebulized area. In fact, the percentage of satisfied people rose from 33% to 57% and those wishing for drier air decreased from 42% to 20%. Paradoxically, the number of respondents wishing to experience wetter conditions increased in the mist.

In terms of wind, most people complained about insufficient breeze outside of the spray and 72% felt a pleasantly airy microclimate under it, especially between 12pm and 2pm. Preference votes did not change much.

Conversely, both solar sensation and preference changed dramatically: almost the entire human sample (80.6%) felt strong solar radiation outside of the mist of droplets, while the same percentage felt a pleasant or even a weak solar warmth in the middle of it, possibly due to the shading action of water droplets [30].

In Rome (Fig. 5), 90.6% of people voted between slightly cool and slightly warm under the spray against more than 50% of people feeling hot or very hot outside of the mitigated area. Beneath the nebulizers, no one complained of hot or very hot conditions: only a very limited (<8%) portion of interviewees reported even slight warmth.

During the 12 - 2pm window, 94% of people taking the test claimed conditions were comfortable beneath the water mist (TSV_s between -1 and +1) and 0% voted +2 or +3. In contrast, 76% of them affirmed conditions were uncomfortable ($TSV\_u \geq 2$) in the unmitigated surrounding area. This demonstrated that evapotranspiration and solar shading from plants were insufficient overheating countermeasures, whereas with water nebulization in place, the thermal sensation was 1-2 votes closer to neutrality.

Humidity sensation was not significantly affected by nebulization, since, both within and outside of the mist, more than 80% of votes were equally distributed between pleasant and humid. This was not so for humidity preference. Whereas a considerable 47% wished for drier air outside of the spray, especially in the morning, less than 15% had the same desire while in the mist. In fact, about 63% of respondents expressed no need for any change, regardless of the time of day.

Wind preference was less sensitive. 80% of people felt good beneath the spray and about 30% preferred the unmitigated zone. Again, the desire for the concentrated droplet cloud outweighed the need for stronger convective heat removal.

Finally, in terms of solar radiation, both sensation and preference were bent considerably. While 53% of people experienced strong irradiation outside the spray, with 43% claiming it was reduced, only 8.6% gave the same rating while under the spray, with the vast majority (72%) changing their opinion to a pleasant sensation and 65.5% asking for no modification. This was particularly so in the morning and between 12 and 2pm.

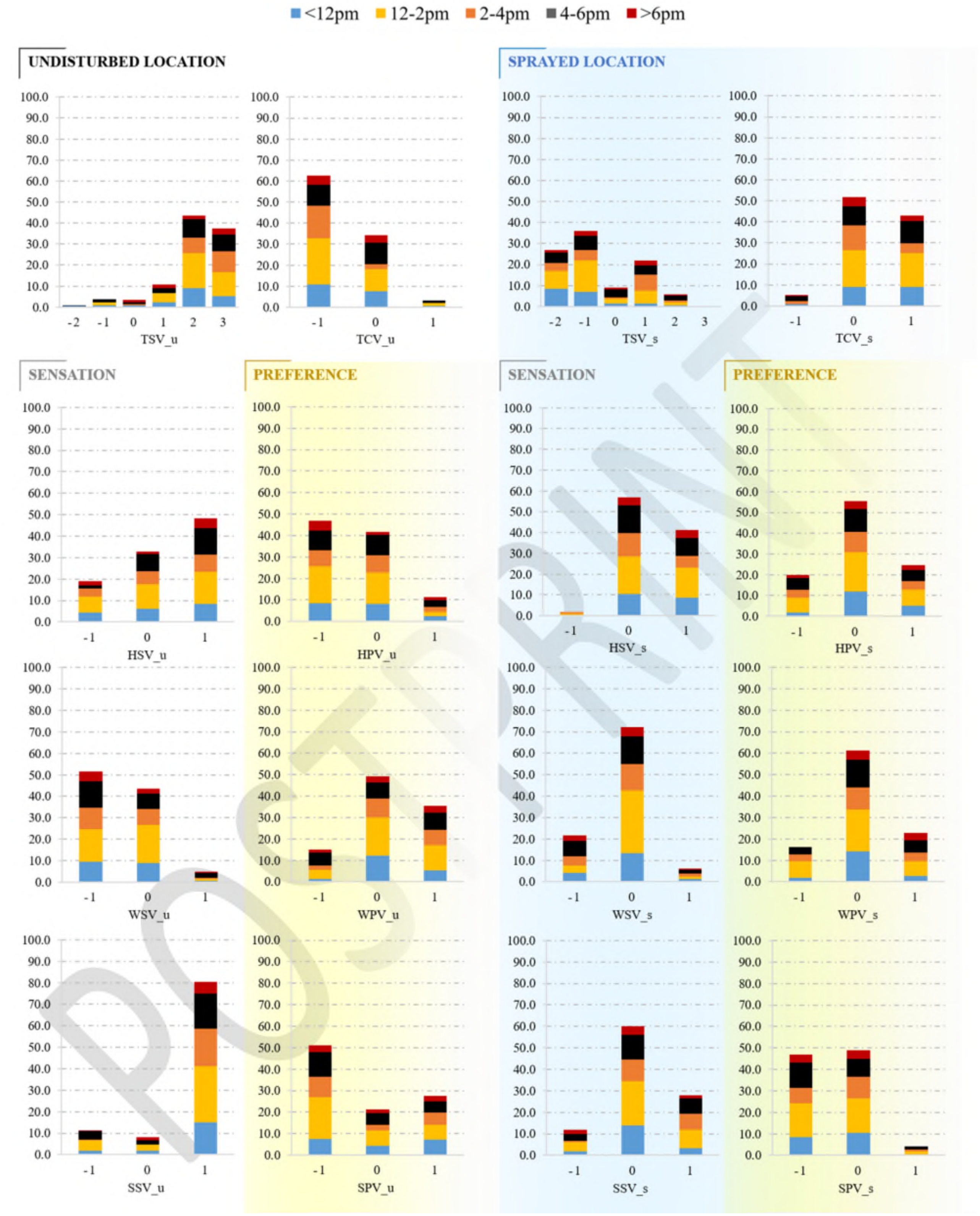


Fig. 4. Percentage frequency of comfort votes at different times of day in Ancona.

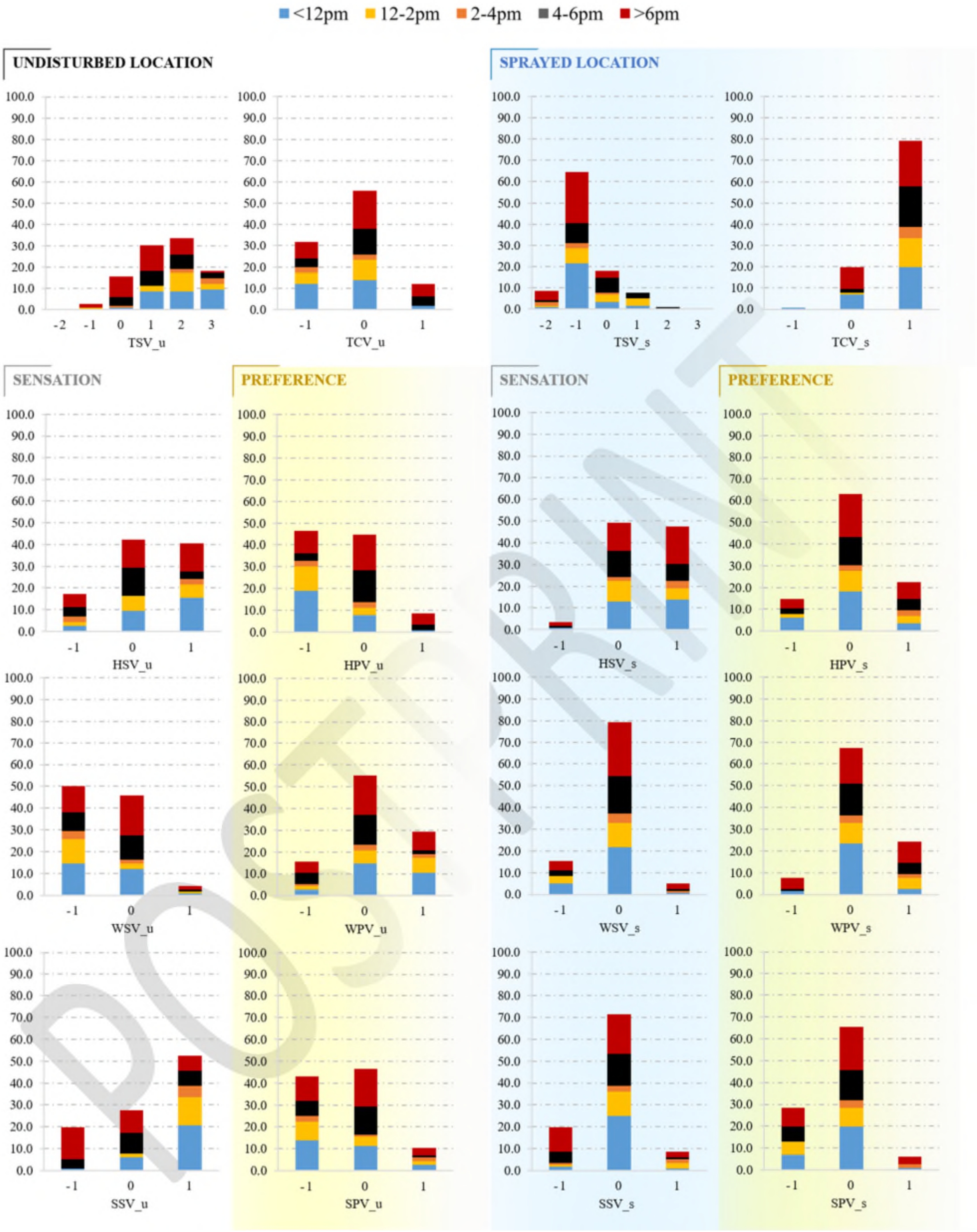
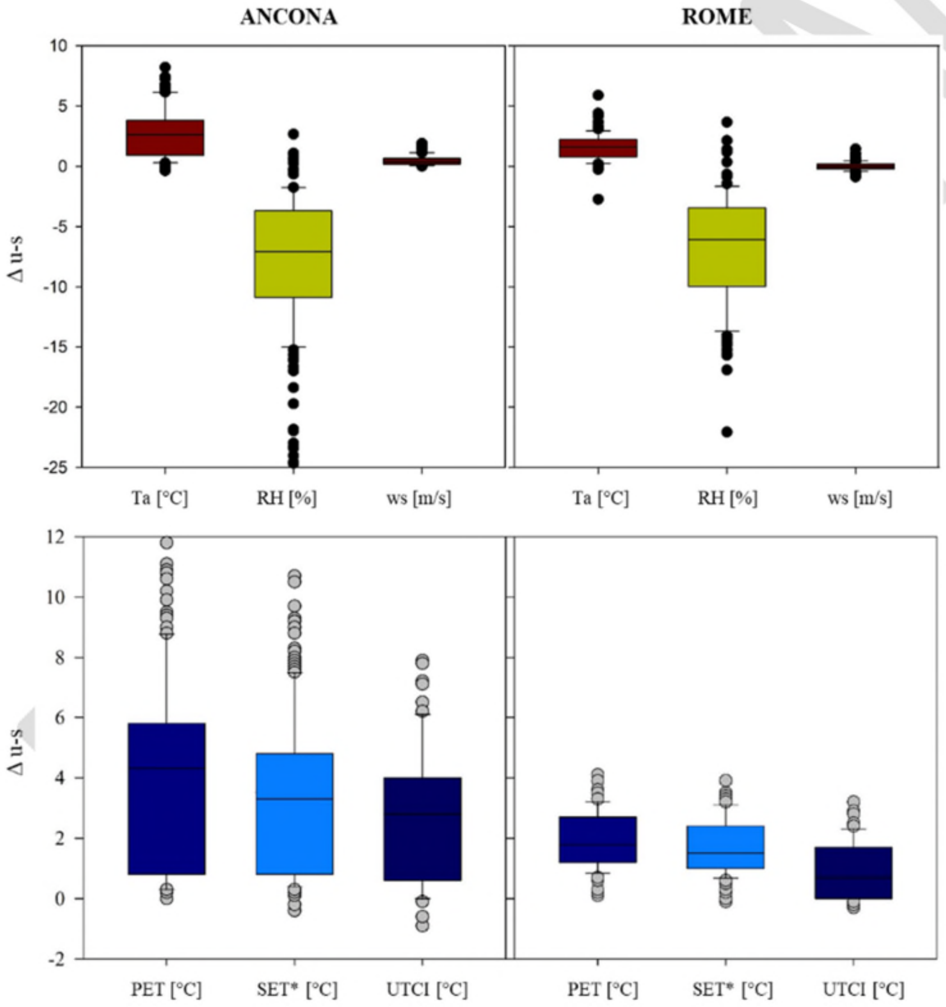


Fig. 5. Percentage frequency of comfort votes at different times of day in Rome.

3.2 The role of environmental variables

Fig. 6 statistically compares the two tested locations using the meteorological data at the time of the questionnaires: under the spray, the temperature drop exceeded 8°C in Ancona and touched 6°C in

Rome, while the relative humidity increased by nearly 7%, on average. The other parameters were generally comparable. The Universal Thermal Climate Index (UTCI) exhibited a maximum reduction in the misted area, compared to the untreated surroundings, of up to 7.9°C in Ancona and 3.3°C in Rome, in line with the results of Montazeri at al. [25,27]. The average decreases were 2.8°C and 0.9°C. The huge discrepancy between the two locations largely depended on the different sky view factor (0.87 in Ancona *versus* 0.48 in Rome) and vegetation coverage. Similar trends were also computed for PMV, PET and SET* (see Fig. 7) using RayMan Pro software [59].



ANCONA	Δ Ta	Δ RH	Δ ws
MAX	8.2	2.7	1.9
MIN	-0.4	-24.7	0.0
MEAN	2.8	-7.7	0.5
DEV.ST	2.1	5.7	0.4
99P	7.4	2.5	1.7
MEDIAN	2.6	-7.1	0.4
IQR	2.9	7.2	0.5

ROME	Δ Ta	Δ RH	Δ ws
MAX	5.9	3.7	1.4
MIN	-2.7	-22.1	-0.9
MEAN	1.6	-6.8	0.0
DEV.ST	1.1	4.6	0.4
99P	4.4	2.0	1.0
MEDIAN	1.6	-6.1	0.0
IQR	1.4	6.5	0.4

ANCONA	Δ PET	Δ SET*	Δ UTCI
MAX	11.8	10.7	7.9
MIN	0.0	-0.4	-0.9
MEAN	4.3	3.5	2.8
DEV.ST	3.0	2.6	2.1
99P	11.7	10.4	7.9
MEDIAN	4.3	3.3	2.8
IQR	5.0	4.0	3.4

ROME	Δ PET	Δ SET*	Δ UTCI
MAX	4.2	3.9	3.3
MIN	0.1	-0.2	-0.4
MEAN	2.0	1.7	0.9
DEV.ST	0.9	1.0	0.9
99P	4.0	3.9	2.8
MEDIAN	1.8	1.6	0.7
IQR	1.5	1.4	1.5

Fig. 6. Environmental differences between the unmitigated and mitigated locations (Δ u-s): general statistics on the temperature, humidity and wind gradients along with the impacts on comfort metrics.

The relationship between the thermal votes, especially those relating to sensation (TSV, HSV, WSV, SSV, TCV), was assessed through the non-parametric Spearman correlation test considering a significance level of 0.01. Fig. 7 displays the colour-mapped matrices of correlation strengths, together with the correlation coefficients. Correlations with p-value > 0.01 were omitted (blank cells), since they are irrelevant.

The graphs highlight a significant relationship of SSV to TSV and TCV in all cases except for the nebulized area in the Roman park: as a rule of thumb, when SSV increased, TSV tended to increase, with correlation coefficients of 0.37, 0.29, 0.51 in Ancona in the undisturbed and nebulized areas and in the Roman undisturbed area, respectively. Conversely, TCV decreased (correlation coefficients of -0.33, -0.27, -0.37 as above). Furthermore, a significant relationship was found between TCV and TSV in the same cases (coefficients between -0.34 and -0.46).

On the other hand, in the Roman nebulized area, TSV was related to WSV with a correlation coefficient of -0.30 (when WSV increased, TSV decreased), whereas in the unmitigated area it was related to HPV (-0.24).

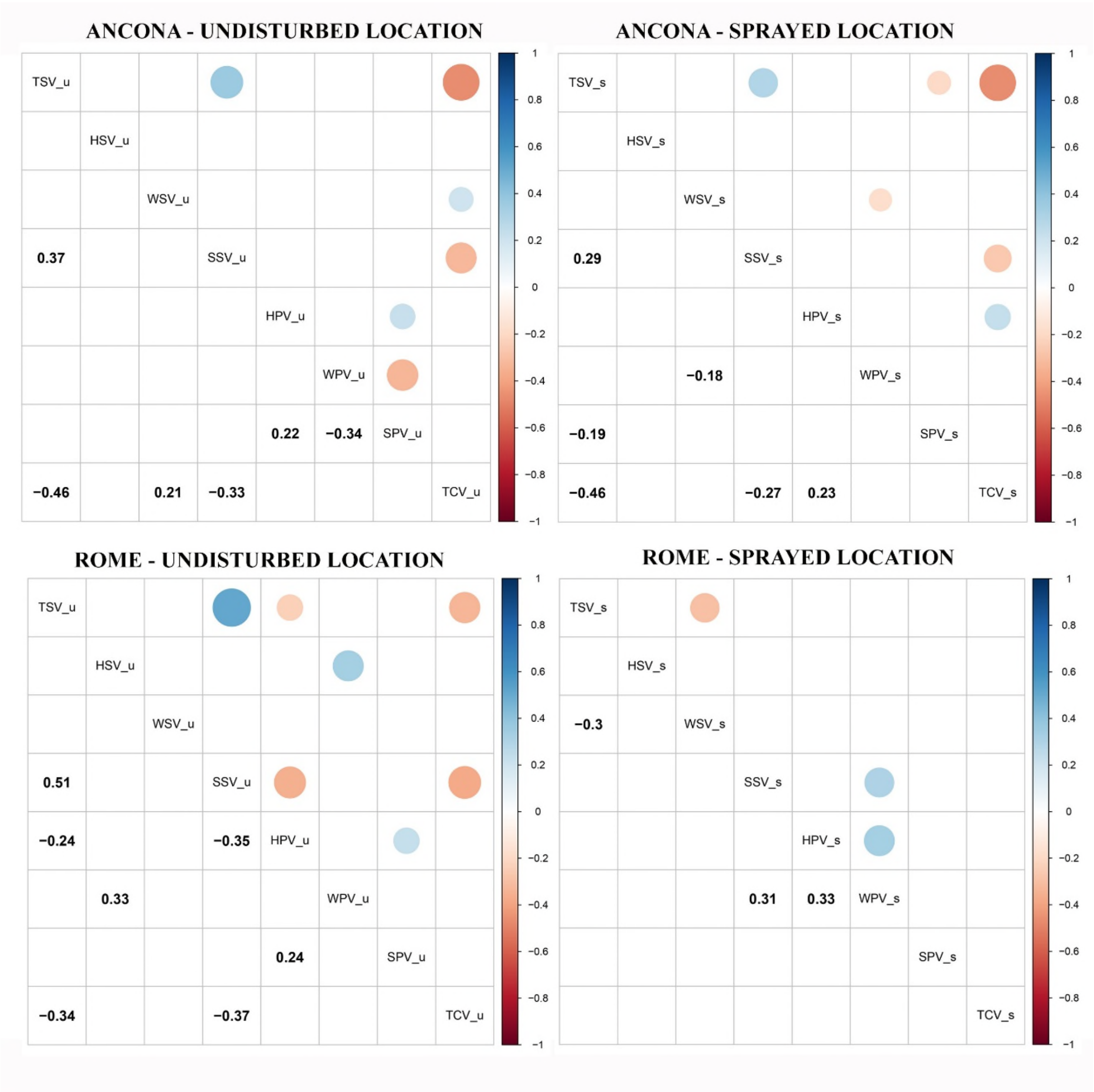


Fig. 7. Correlation matrices for comfort votes: Ancona and Rome (top and bottom) undisturbed and misted areas (left and right), coloured according to the positive (blue) or negative (red) value of the correlation coefficients and sized proportionally. Explicit coefficients are diagonally specular.

Merging all statistically significant results for the misted area, we observed that:

- in Ancona, the average TSV never crossed the +2 limit, except under very high dry-bulb temperatures (32-35°C), solar radiation (>900W/m^2) and wind speed (2.4-4.8m/s). Conversely, cool/cold sensations only occurred for medium-low wind speeds (less diluted mist) and mild solar radiation or air temperature;

- in Rome, no overheating was experienced throughout the survey. Slightly excessive cooling occurred on two major occasions: (1) around 27-28°C with the sun beating down over 900W/m^2 and very dry conditions, thus when evaporation was stimulated, (2) below 26°C in overcast and stagnant conditions when the mist was less diluted. In the unmitigated zone, severe overheating occurred under all recorded combinations of environmental parameters;
- humidity was the crucial and most controversial parameter in terms of sensations and preferences: whereas for sun and wind the relieving effect of spraying water was apparent, the satisfaction with moisture concentration largely depended on the concomitant wind speed and solar radiation. Indeed, still air and mild solar radiation (100-700 W/m^2) were precursors for potential discomfort as people could feel wet and clammy.

3.2 The role of personal variables

Typically, clothing insulation and metabolism strongly affect comfort votes [60]. However, the results of the non-parametric Kruskal-Wallis H test showed that TSV was not significantly different between various garments and metabolic rates, indicating that these may not have influenced thermal sensation in the considered areas and conditions.

Nonetheless, we observed that preferences and sensations fluctuated in proportion to metabolic rate (different heat generation and relative velocity with the air …) and thermal insulation (different sweat risk, skin sensitivity …). All respondents wearing the equivalent of more than 0.5clo and engaged in 1.2-1.5met activities affirmed conditions were humid. The preference was milder, only exceeding -0.5 (desire for drier air dominant over desire for no variation) for very sedentary activities.

3.3 The role of height

Before embarking on the analysis of feedback in relation to the height of respondents, the vertical cooling and humidification profile from the injections was investigated, using the additional measurements collected on 30 August in Rome at 1.1m, 1.7m, 2.1m e 2.5m above the ground.

A mild increase for both cooling and humidification was detected from 2.5m downwards peaking at the 2.1m probe (-0.4°C and +1.7% in a 0.4m space). From there on, a trend reversal occurred with a steeper slope: the temperature gain was +0.9°C from 2.1m to 1.7m and +1.4°C from 1.7m to 1.1m, while the corresponding humidity deficit was -3.6% and -3.4% on average.

Consequently, the regression analysis focused on non-linear, peak statistical distributions. Finally, the 4-parameter Lorentzian equation produced a somewhat perfect fit. This statistical law has already been applied to describe the size spectrum of rain drops with excellent correspondence [61].

In Fig. 8 the general regression form is given, together with the four parameters (a,b, x_0 and y_0) made explicit in terms of the average temperature and humidity profiles. The computed values match the measured means to the fourth digit.

To the best of the authors' knowledge, this is the first time the vertical profile of evaporative cooling from overhead nebulization has been mathematically characterized as a function of the distance from the ground, based on multi-point measurements in real urban contexts.

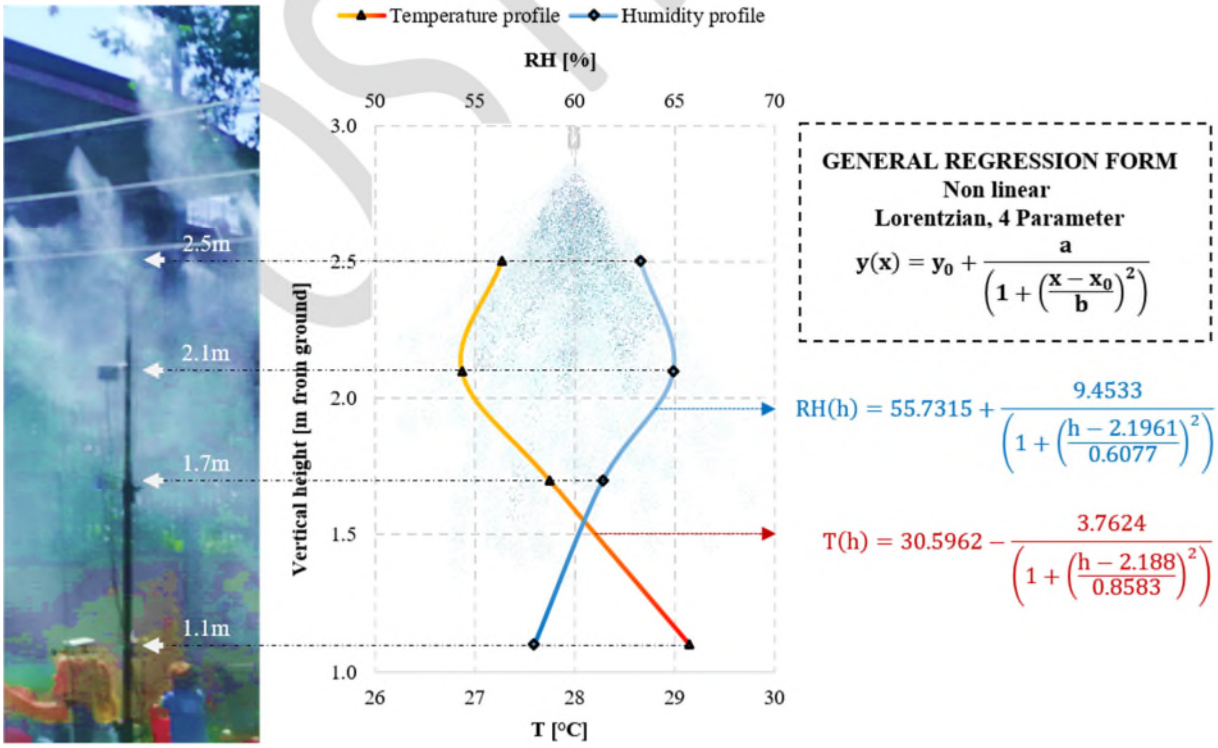


Fig. 8. Average vertical profiles returned by the four thermohygrometers (whose assembly is shown on the left) together with the Lorentzian regression lines and equations.

On the above premises, we expected stronger feedbacks from interviewees taller than 1.85m in both locations: indeed, only passers-by of that height reported -2 thermal votes beneath the spray. In contrast, the results of the non-parametric Kruskal-Wallis H test showed that TSV did not differ significantly between the various heights of the interviewees. However, in Ancona (where the nebulizing system was suspended 3.3m above the ground) the most satisfied interviewees were those at a height of 1.7-1.8m, whereas in Rome (nebulizing system at 2.8m) those below 1.7m and especially those sitting under the spray expressed full appreciation. Hence, most people felt comfortable approximately 1.5m away from the water injection, which appears to be the optimal reciprocal distance between users and nozzles. This finding was further supported by the extra comments left by the interviewees (last section of the questionnaires): in Ancona more than 30% of people asked for a lower injection and 14% for a stronger one. Conversely, in Rome, almost no one asked for a height modification. Nevertheless, since measurements were only performed at two locations, such design indications may require further verification.

3.5 Association rules

In Rome, repetitive patterns were much stronger, because of the limited environmental variability. Equal combinations of breeze and solar irradiation occurred regularly given the wind-breaking action of both the local urbanscape and vegetation, whereas in Ancona cloudy and windy days extended the range of cases and made it harder to observe consistent feedback. As a result, few high-confidence relationships (95%) emerged.

Most of the dominant associations, identified via the FP-Growth mining algorithm, align with the results discussed in the previous paragraphs. However, some additional useful information emerged.

In Ancona, the most supported rules (support≥0.18) linked solar sensation in the undisturbed location (SSV_u) to the concomitant moisture content: people reported strong solar irradiation with drier air. This is a substantiated fact. Indeed, it has been shown that empirical relationships between solar-radiation intensity and hours of sunshine return much better estimations, if relative humidity is incorporated as a decrement factor (see [62] for the relevant equations). Turbulence intensity was also found to play a key role: as this decreased by 40% (high mean wind speed compared to the standard deviation) both under the spray and in the undisturbed location, the chances of feeling the scorching sun were far greater. This might suggest that overhead nebulizing systems should be implemented in stagnant places where solar radiation is the main trigger for overheating.

In Rome, the most supported rules (support≥0.2) regarded thermal comfort under the spray (TCV_s). People felt comfortable in a variety of environmental combinations, involving very low humidity (<40%), moderate wind speed (1.2-2.4 m/s) and dry bulb temperature in the 30-32°C range. Women regularly felt more satisfied under the spray, especially those dressed in light clothing and seated. This is not a trivial point. Although females typically show a stronger negative reaction to hot conditions [63] and thus appreciated the mist, they also show less tolerance to rapidly changing environments due to the larger ratio of body surface to body mass [64]. Thus, the mist caused no sizeable discomfort due to thermal gradients. In terms of height, the 1.5-1.7m group frequently gave a pleasant feedback for solar radiation. This might suggest that the mist exerts the best solar attenuation action between 1 and 1.2m from the nozzles.

Humidity was the key-player in both locations and in relation to all comfort metrics. Most association rules refer to levels below 40% and 40-50%. Indeed, with lower relative humidity under the spray, the perception of both wind and sun improved. Sun preference was the only metric that was independent of humidity, but directly related to all the other environmental variables and to the time of day. Conversely, humidity preference under the spray depended on solar irradiation, with sunny conditions (Ioh_s=700-900 W/m^2) tending to stop the desire for either drier or wetter air.

In terms of wind, in Rome, still air conditions (<0.3m/s) led to votes of slightly cool beneath the spray, medium-low speeds (0.6-1.2m/s) were the most appreciated (WSV_s=0) and medium-high speeds (ws*_s=1.2-2.4 m/s) more frequently voted as comfortable (TCV_s=1), with no preference for either sunnier or cloudier contexts. Interestingly, wind speed never appeared in the association rules for Ancona, either in mean terms or as turbulence. This suggests that, as the speed variability increases, the chance to accurately predict comfort beneath the spray decreases. All these considerations suggest that the nebulizing system works better with a dominant and steady light breeze, between approximately 1 and 2 m/s.

4. Conclusions

This study aimed to 1) quantify the outdoor comfort benefit of implementing water nebulization in urban open spaces and 2) experimentally substantiate comfort-optimal design guidelines.

We devised, installed and monitored a customized web of 24 overhead nebulizers in two Italian urbanscapes: the coastal city of Ancona, representative of high humidity atmospheric conditions and the capital, Rome, representative of sweltering, still air conditions and an intense urban heat island effect. The campaigns took place on the university terrace and in a green park, respectively. Measurements and personal feedbacks (comfort questionnaires) were collected.

A meteorological station was used to characterize the reference locations, representative of unmitigated conditions while a suite of five thermohygrometers was located right beneath the sprayed zone, together with a globe thermometer. A suite of 8 comfort indicators was used for both the reference and the mitigated areas. Special care was devoted to the response to each environmental factor (temperature, humidity, sun, wind …).

The relationship between thermal response votes was assessed through the non-parametric Spearman correlation test, while the non-parametric Kruskal-Wallis H test was applied to determine whether the thermal sensation vote varied with personal variables. Additionally, the dataset was mined (FP-Growth Algorithm) to detect frequent association rules (95 % confidence).

The main results are briefly outlined below:

- in the misted area, the temperature and UTCI dropped by -8.2°C and -7.9°C respectively, with a mean humidity premium of about 7%. Consequently, while no one felt comfortable outside of the mist, the entire human sample felt comfortable or acceptably satisfied with the mitigated environment;
- the vertical cooling and humidification profiles obeyed a Lorentzian distribution, peaking at about 0.5m of the injection. Apparently, those standing approximately 1.2-1.5m from the water injection benefited most from both cooling and solar attenuation;
- slightly excessive cooling was experienced on three occasions: (1) when the evaporation was emphasized (temperature over 27°C, scorching sun and very dry conditions); (2) with stagnant air and low irradiation; (3) when multiple evaporative processes had a cumulative impact (presence of greenery). In these cases, a smart controller calibrating the injections to the contextual boundary conditions (as developed in [16]) could be decisive;
- the water mist bent the way respondents related with humidity, wind and sun. 80.6% and 72% of respondents reported a pleasant or even a weak solar warmth in the middle of the mist, in both locations. Thus, misting systems may be well suited to highly irradiated sites;
- paradoxically, people were much more satisfied with the humidity level and the sensation of wetting under the mist;
- the nebulizing system worked better with a dominant and steady light breeze of between approximately 1 and 2 m/s;
- in terms of personal variables, the sense of stickiness and clammy air was exacerbated above a certain level of activity and clothes covering given the higher risk of sweating. Women more regularly and more strongly expressed their satisfaction with the nebulized environment.

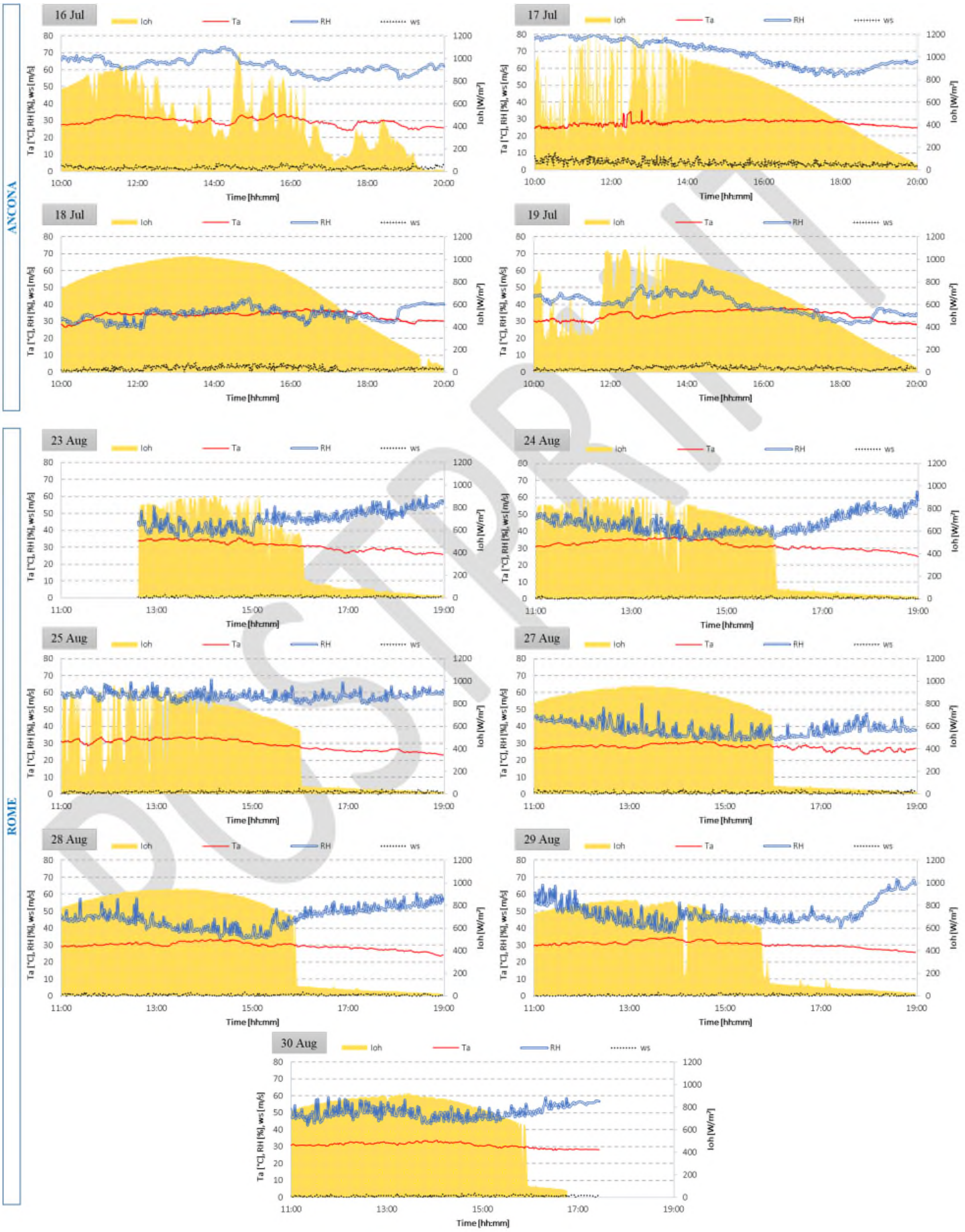
Overall, this study allowed to better understand how water-based mitigation technologies impact on outdoor comfort in urban settings. Some design guidelines were discussed in relation to the experimental evidence. Many points are worth further investigation, such as the interplay between nebulization and evapotranspiration from plants, the effective spatial extension of the cooling action and the potential combination with other mitigation technologies.

Acknowledgements

The authors warmly thank the Italian national agency for new technologies, energy and sustainable economic development (ENEA) - under the PAR 2017 funding - for providing the resources to build the prototype and for granting the monitoring authorizations.

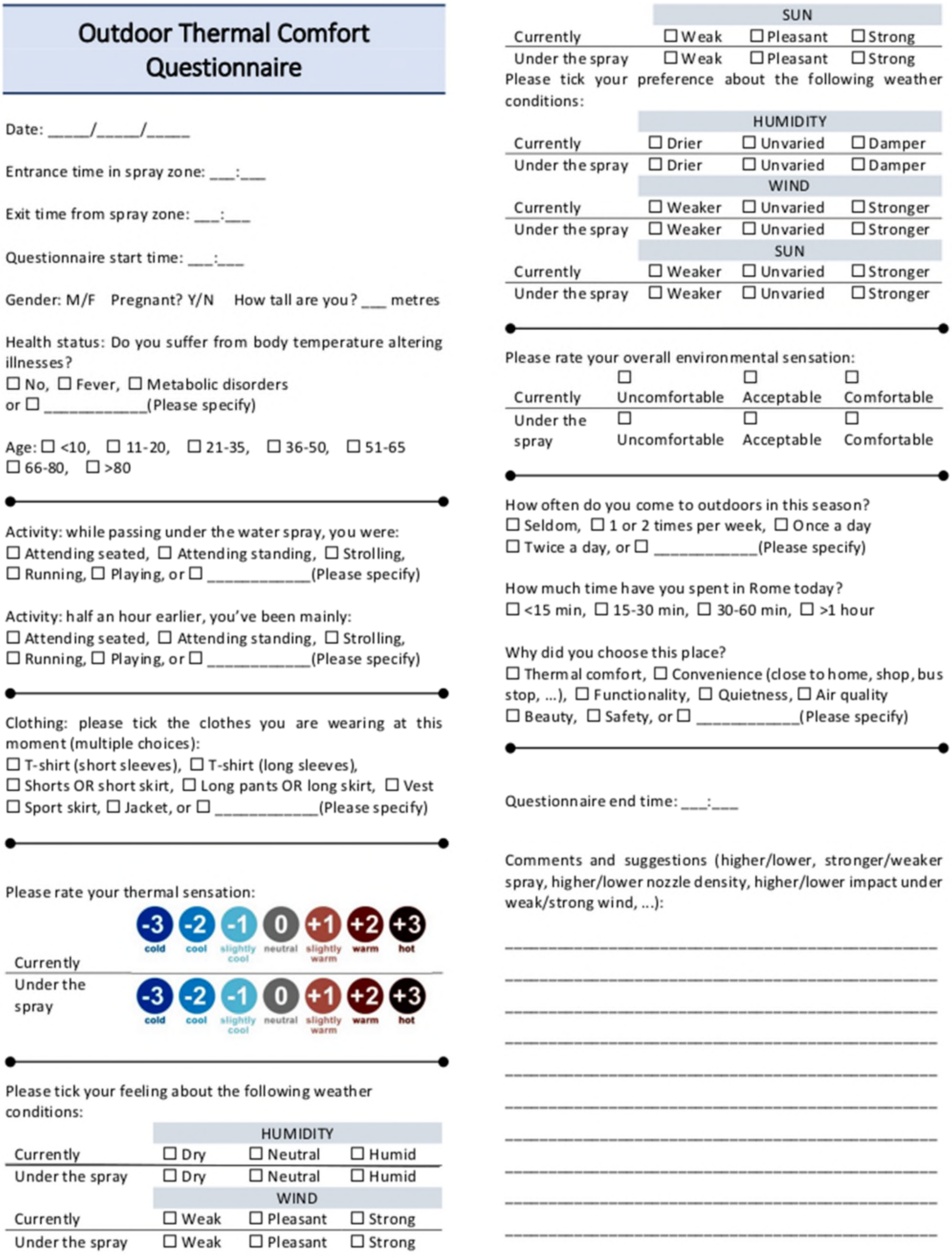
Appendix A

Meteorological profiles during the two monitoring campaigns ((Ta=air temperature, RH=relative humidity, ws=wind speed, Ioh=global horizontal irradiation)



Appendix B

Questionnaire structure (example of the one distributed in Rome).



Outdoor Thermal Comfort Questionnaire

Date: ____/____/____

Entrance time in spray zone: ___:___

Exit time from spray zone: ___:___

Questionnaire start time: ___:___

Gender: M/F Pregnant? Y/N How tall are you? ___ metres

Health status: Do you suffer from body temperature altering illnesses?
☐ No, ☐ Fever, ☐ Metabolic disorders
or ☐ __________(Please specify)

Age: ☐ <10, ☐ 11-20, ☐ 21-35, ☐ 36-50, ☐ 51-65
☐ 66-80, ☐ >80

Activity: while passing under the water spray, you were:
☐ Attending seated, ☐ Attending standing, ☐ Strolling,
☐ Running, ☐ Playing, or ☐ __________(Please specify)

Activity: half an hour earlier, you've been mainly:
☐ Attending seated, ☐ Attending standing, ☐ Strolling,
☐ Running, ☐ Playing, or ☐ __________(Please specify)

Clothing: please tick the clothes you are wearing at this moment (multiple choices):
☐ T-shirt (short sleeves), ☐ T-shirt (long sleeves),
☐ Shorts OR short skirt, ☐ Long pants OR long skirt, ☐ Vest
☐ Sport skirt, ☐ Jacket, or ☐ __________(Please specify)

Please rate your thermal sensation:

Currently	-3 cold	-2 cool	-1 slightly cool	0 neutral	+1 slightly warm	+2 warm	+3 hot
Under the spray	-3 cold	-2 cool	-1 slightly cool	0 neutral	+1 slightly warm	+2 warm	+3 hot

Please tick your feeling about the following weather conditions:

	HUMIDITY		
Currently	☐ Dry	☐ Neutral	☐ Humid
Under the spray	☐ Dry	☐ Neutral	☐ Humid
	WIND		
Currently	☐ Weak	☐ Pleasant	☐ Strong
Under the spray	☐ Weak	☐ Pleasant	☐ Strong
	SUN		
Currently	☐ Weak	☐ Pleasant	☐ Strong
Under the spray	☐ Weak	☐ Pleasant	☐ Strong

Please tick your preference about the following weather conditions:

	HUMIDITY		
Currently	☐ Drier	☐ Unvaried	☐ Damper
Under the spray	☐ Drier	☐ Unvaried	☐ Damper
	WIND		
Currently	☐ Weaker	☐ Unvaried	☐ Stronger
Under the spray	☐ Weaker	☐ Unvaried	☐ Stronger
	SUN		
Currently	☐ Weaker	☐ Unvaried	☐ Stronger
Under the spray	☐ Weaker	☐ Unvaried	☐ Stronger

Please rate your overall environmental sensation:

Currently	☐ Uncomfortable	☐ Acceptable	☐ Comfortable
Under the spray	☐ Uncomfortable	☐ Acceptable	☐ Comfortable

How often do you come to outdoors in this season?
☐ Seldom, ☐ 1 or 2 times per week, ☐ Once a day
☐ Twice a day, or ☐ __________(Please specify)

How much time have you spent in Rome today?
☐ <15 min, ☐ 15-30 min, ☐ 30-60 min, ☐ >1 hour

Why did you choose this place?
☐ Thermal comfort, ☐ Convenience (close to home, shop, bus stop, ...), ☐ Functionality, ☐ Quietness, ☐ Air quality
☐ Beauty, ☐ Safety, or ☐ __________(Please specify)

Questionnaire end time: ___:___

Comments and suggestions (higher/lower, stronger/weaker spray, higher/lower nozzle density, higher/lower impact under weak/strong wind, ...):

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