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Effect of vegetation cover on thermal and visual comfort of pedestrians in urban spaces in hot and dry climate

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Abstract

The effect of climate on the use of outdoor spaces in urban environments is particularly important for activities that occur in these areas. The consideration of the thermal and visual outdoor conditions in cities is increasingly important for the well-being of man and the use of public spaces. Vegetation zones play a significant role in the city through their visual appeal and their regulation of microclimates. Considering the microclimatic modification produced by vegetation, the objective of this research is to compare the performance of areas shaded by five different types of tree coverage, including an open area without vegetation, located in a hot and dry climate. The methodology is based on a combination of in situ measurements and thermal and visual comfort surveys. Measurements of air temperature, air humidity, wind speed, solar global radiation, luminance and the sky view factor combined with comfort surveys were performed during summer in five different areas of a square in the city center of Constantine in Algeria (a hot and dry climate). The results indicate that the percentage of tree coverage of a space is a highly important metric to assess outdoor comfort in a hot dry climate and that it influences mainly the use of outdoor recreational areas. Dense vegetation cover optimises the microclimatic environment for pedestrians' thermal and visual comfort in urban spaces, under these climatic conditions.

Keywords: Tree cover; thermal sensation: visual sensation: solar energy; outdoor public space.

1. Introduction

Urban public spaces are fundamental for the social life of cities due to their capacity to serve as meeting spaces and be conducive to interactions among the public. Moreover, public spaces play a large role to define the quality of life experienced by citizens. For this reason, it is essential that urban public spaces be comfortable and attractive (see figure 1), as they are places where collective values are built. However, the poor design of these spaces sometimes contributes to increased isolation and social exclusion, depending on physical environment and social fabric, which evidently affect the behaviour of the users in external spaces [1].

An English experiment, investigate with the participation of 1431 interviewers, examined how thermal comfort affects use of these spaces, and it demonstrated that a relationship existing between microclimatic conditions (temperatures, solar radiations ...) and the number of visitors in public places [1]. Other researchers have shown that quantitative approach is not sufficient for the study of comfort in outdoor areas. Methods of qualitative criteria are also needed in this area of research [3, 4].

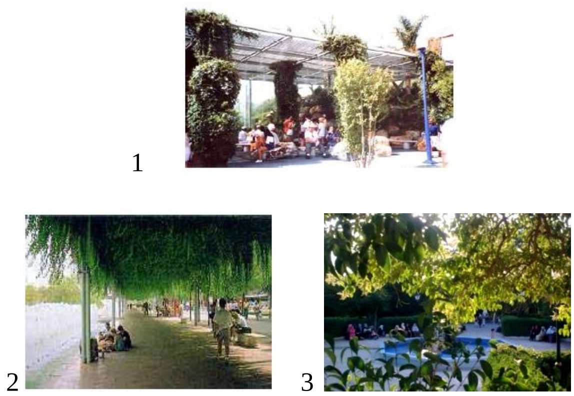

Figure 1: Public space from expo' 92 in Seville (1 & 2) and a square in Constantine (3)
Source: Grupo de termotecnia, 1994 [2], and Louafi, 2013

The benefits of green spaces in urban areas are recognised by many authors. Where, vegetation can modify the microclimate (light, heat, wind, and humidity) and it can influence people's perceptions of these spaces [1, 3-5]. Trees and vegetation embellish the cities and improve the citizens' quality of life. Trees planted along streets, in parks and around houses or shops or in the green areas in the city also improve the quality of air and water. Urban vegetated areas offer recreational zones, and they make districts more pleasant [6].

The purpose of the present research is to assess whether people located under various types of tree coverage experience comfort or stress in open spaces with hot-dry climate. A specificity of this study is; the use of a quantitative analysis with micrometeorological measurements together with a qualitative analysis via comfort questionnaire surveys. The overall goals of this research are the following:

(1) To investigate the quantitative effects of five different stations with various tree coverage on thermal and visual conditions in outdoor spaces through in-situ measurements.
(2) To discuss whether tree coverage affects people's thermal and visual comfort in a hot-dry climate using comfort questionnaire surveys.
(3) To highlight the role of degree of tree coverage and the use of recreational areas in a hot-dry climate.

2. Vegetation effects on thermal and visual environments

Air temperature and air humidity cannot normally be significantly modified by landscape elements and design at large urban scales. However, at the local scale, modifications can be achieved by introducing new elements; such as trees or water fountain, especially in dense environments, to generate specific microclimates [7]. Vegetation is an essential landscapes element to improve the microclimate in architectural and urban projects. Previous studies on the climatic effects of urban vegetation provide useful of greening for urban designers. The climatic benefits of urban vegetation are assessed either as a function of their effects on meteorological factors (e.g., air temperature or win speed) in urban public spaces or on the induced energy savings in buildings as a result of less cooling and/or heating loads.

Four main ways to modifying the microclimate through soft landscape elements, especially trees: (1) modifying the solar radiation intensity, (2) modifying the reflected radiation from the ground and other surfaces, (3) modifying the relative humidity and (4) modifying the wind [7, 8]. The principal microclimatic effects of vegetation on thermal and visual environments are provision of shade and reduction of solar radiation. Vegetation intercepts solar radiation, which is an important design element of outdoor comfort. Vegetation possesses two other properties that affect the microclimate: humidification (evapo-transpiration) and windbreak [9]. With the effects of shade and evapo-transpiration, trees can reduce the air temperature under their coverage. Indirectly, vegetation also acts as a medium to trap water inside the soil. Any use of vegetation for improving the microclimate must exploit these properties judiciously according to site comfort requirements [10].

The relationship between air temperature and the presence of trees in an urban environment has been studied by many researchers around the world [9, 11-23]. A key finding is that, in a hot climate, air temperature in open spaces without trees is always higher than in vegetated environments [21, 3-26]. In a hot climate, trees usually contribute to cooler summer air temperatures, and this effect on microclimate depends on the size of the vegetated area [21].

In a hot-humid climate, tree-shaded outdoor areas improve human thermal comfort [27]. The cooling effect of trees in small urban green sites, courtyards and streets is approximately 1 °C and up to 3 °C during the hottest hour of the day in a subtropical location [16]. The importance of shade in outdoor spaces under shade of trees or buildings is demonstrated, where 93 % of people visiting a public square in summer in Taiwan prefer shade [28]. Further to that a study by Louafi and Abdou (2012 and 2013) in an open urban space with masse, row trees and mineral one improving effect of shade on using space. Results show that controlling SVF and presence of trees can reduce air temperature [23, 29]

A canyon street with various SVF and presence or absence of row trees are investigated, results improve importance of shade on microclimate and thermal human comfort during overheated period [30]. In a hot-dry climate, Grimmond et *al.* [13] found in that under the tree-vegetated suburban area in Sacramento, the air temperature increase about 5 °C to 7 °C than in mineral areas. As vegetation can block a wide spectrum of the incident solar radiation, the related shading effect of vegetation affects thermal and visual environments. In this respect, the presence of trees is an important factor in the radiative exchange process between surfaces and people.

While 80 % of the visible wavelength of solar energy is absorbed by the leaves of plants for photosynthesis, 80 % of the solar infrared radiation is reflected or transmitted through the leaves (see figure 2). It is therefore important to account for, on the one hand, the shading effect of trees on visual and thermal comfort and, on the other hand, the influence of reflected and transmitted solar infrared radiation on the energy budget of humans and buildings in their surroundings [8, 31, 32].

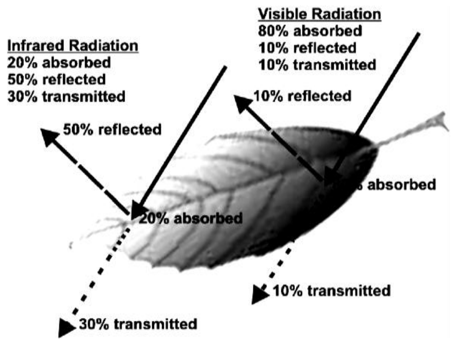

Figure 2: Leaf absorption, transmission and reflection [29].

Tree cover modifies the air's humidity by perspiration [33]. Previous studies show that, in a dry climate, vegetation increases the local relative humidity in urban green spaces from 3 % to 6 % compared with spaces without vegetation [17, 23, 34, 35]. Impact of vegetation on visual comfort in urban environments is completely neglected in the literature, in contrast to its influence on thermal comfort.

3. Site investigation

An investigation was conducted in Constantine City (Algeria), which is located at latitude 36.17 north and longitude 07.23 east. Site altitude is approximately 687 m above sea level. Constantine is characterised by a semi-arid climate which is hot and dry in the summer, with an average maximum air temperature about 36 °C occurring at 15h00 and an average humidity of 25 %. In the winter, the area is cold and humid. In addition, solar radiation intensity is high, with clear skies and sunny periods existing during a large portion of the day. The wind direction comes relatively from the North, with an average speed reaching 2.1 m/s at the meteorological station. All these factors contribute to the climatic harshness of the city. Investigation site is located in city centre of Constantine.

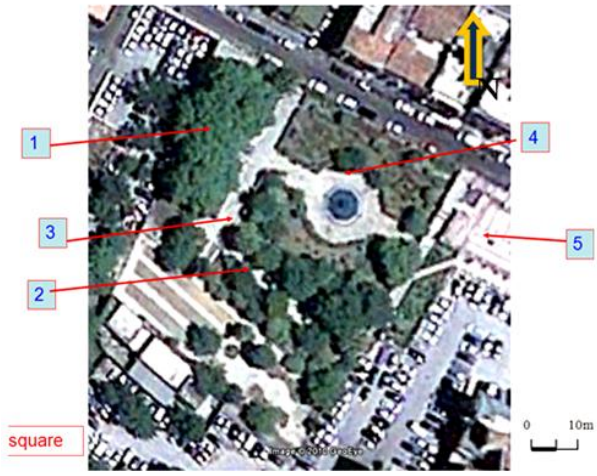

Figure 3: The Square: the selected site and the different stations of the measurements and surveys

Selected investigated location is a recreational space. This square is characterised by stations under various tree cover and an open area without any tree coverage located next to it. Note that in one station of this square, there is also a water fountain. Five stations were chosen by their different vegetal environments represented in this square (see figures 3, 4 and 5). The measurements and comfort surveys were performed under these five types of tree coverage.

Figure 4: View of the vegetal square (left) and the mineral area (right) investigated

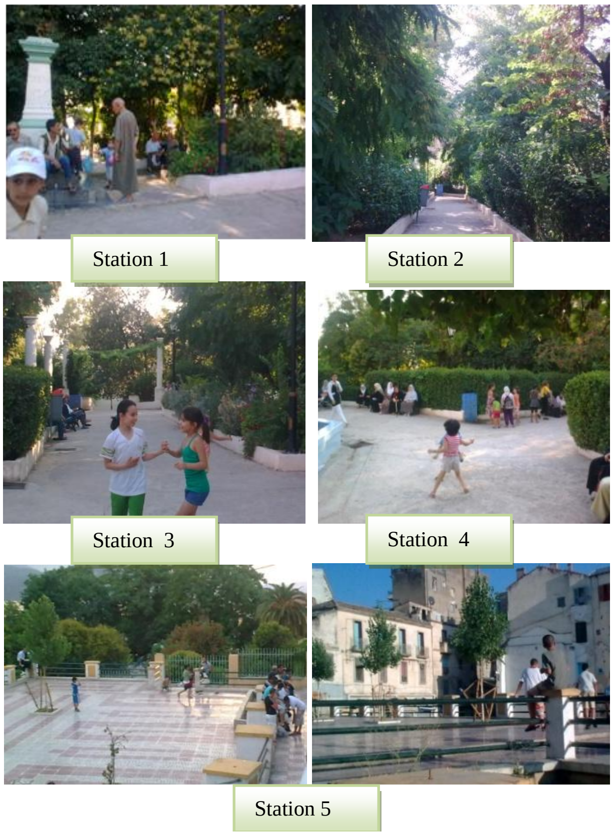

Figure 5: Different stations of areas investigated in the square

4. Methodology

This research aims to highlight the variation of the climatic parameters that vegetation induces on outdoor thermal and visual comfort during overheating periods in hot-dry urban environments also study focalise on effects of tree coverage for the use of recreational spaces. In this way method consists in comparing different spaces around a square in Constantine City (Algeria) by in-situ measurements and comfort surveys. The measurements dynamically assessed five physical parameters (air temperature, air relative humidity, wind speed, global solar radiation and luminance) and also gave a mean value for the sky view factor (SVF). The thermal and visual comfort surveys were undertaken with recreational users.

Measurements and surveys were collected from five stations that were selected according to variation of percentage of vegetation coverage in the square: station 1 = 85 %, station 2 = 65 %, station 3 = 45 %, station 4 = 20 % and station 5 = 0 %. Measurements and surveys were carried out in summer during the month of July 2014, representing the hottest period. The measurements were carried out simultaneously over three weeks. One typical daily cycle was selected in this research to stand for the three-week period to show detailed monitoring results. Air temperature, relative humidity, wind speed, solar radiation and luminance were collected using digital instruments (Multifunction instrument (LM800), Pho-radiometer HD2302.0 with several probes). Remote measurements were taken at a height of 1.5 m and were recorded every 2 hours at each station from 6:00 to 20:00 each day. To determine degree of open sky (SVF), fish-eye photographs were taken at each station 1.5m above ground with a Nikon 8mm fish-eye lens with a picture angle of 180°.

Field comfort surveys of 2200 interviews were conducted in four tree-shaded spaces and an insulated area (without trees) throughout the three-week period during summer 2014. One aim of these surveys was to obtain a better understanding of human thermal comfort response outdoors and to propose an adaptive comfort model for spaces shaded by vegetation in hot-dry summer climates, which will be detailed in a following paper. Qualitative data on the visual and thermal perception of the interviewees were recorded using a questionnaire (see table 1) that was adapted from those used in recent ANSI/ASHRAE indoor studies with some specific items added [36]. For example, questions that enquired about sun/shade preferences were not part of the ASHRAE questionnaire.

Table 1

Questionnaire used in this research

Date and hour	**July 2014**						
Sex	Female			Male			
Age	≤18	18-30	30-45	45-55	≥55		
What is your opinion of the level of comfort in this place?	Day: …	Night: …	Day and night: ….				
During which time of the day do you find the place most pleasant?	The morning						
	At midday						
	After midday						
	All day						
Among these climatic conditions, in your opinion, which is the factor that will cause the most discomfort? (choose one condition)	Strong sunlight						
	An overcast sky						
	High moisture content						
	Strong wind						
	High temperature						
	Other (specify)						
	Very cold	Cold	Neither cold nor hot	Hot	Very hot		
What do you think of the sun at this time?	Prefer more	Neutral	Too much sun				
What do you think of the wind at this time?	Calm	Weak wind	Neutral	Windy	Too much wind		
What do you think of moisture at this time?	Wet	Neutral	Dry				
Do you feel comfortable?	Yes	…………………………………………………………					
	No	…………………………………………………………					
What do you think of the luminosity of this space?	Very dark	Dark	Neither dark nor bright	Bright	Very bright		
Do you feel a sensation of glare when you are looking at some surfaces (reflecting solar radiation)?	No	Surfaces of the ground and the pavement	Construction	Vegetation	Water surface	Urban development	Sky
Does the view from your position affect your appreciation of this site?	No	Somewhat	Yes				

5. Results and discussion

5.1. Air temperature

Figure 6 shows that air temperature evolution during a typical summer day at the five measurement stations. This typical summer day presents the average values measured during a few continuous days. The figure shows that insulated space without trees is warmer from 10:00 to 20h00 than the vegetal areas under different percentage of tree covers, which is consistent with previous studies. Figure 6 also shows that denser vegetation cover, the increase air temperature, which is reduced during the overheating moment of the day. One exception is register for air temperature measured at station 4 (with 20 % of tree cover) is equivalent to the air temperature measured at station 3 (with 45 % of tree cover), and is even lower at 14:00.

Presence of a water fountain and proximity to masse trees and vegetation procure evapo-transpiration at station 4 and participate in lowering air temperature.

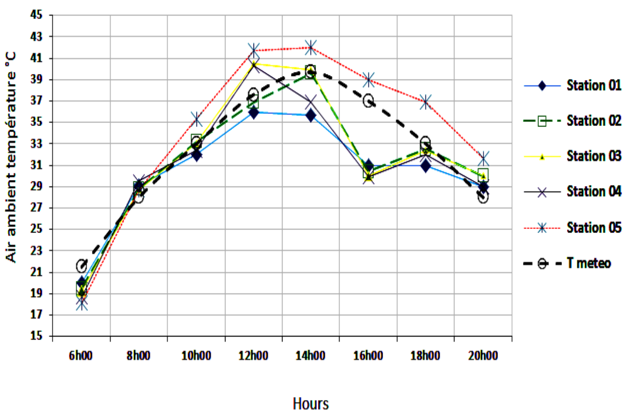

Figure 6: AverageAir temperature at the various stations of measurement during few continuous summer days

According to analyses of results, the mean temperature differences between the insulated space and the four vegetal areas were found very important demonstrated in figure 7.

Results provided a most significant difference in air temperature during the hottest period, between 10:00 and 16:00. These values are coherent with the results of a previous study on urban vegetal areas in the hot-dry climate mentioned above [22, 23]. Figure 7 shows that the space with the highest tree coverage is 6.7 °C cooler than the open space at 12:00 and is 4 °C cooler at 14:00. Note also that water fountain combined with tree coverage of 20 % can lower air temperature by 2.2 °C at 12:00 and 2.4 °C at 14:00 compared with the open space. Figure 8 demonstrates that air temperature has a negative correlation (R= 0.872 à 12:00) within the percentage of tree coverage.

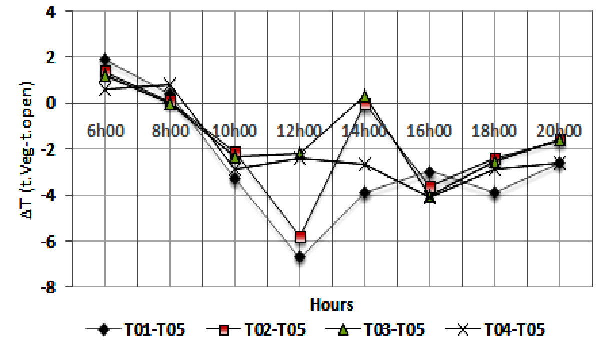

Figure 7: AverageAir temperature at the various stations of measurement during few continuous summer days

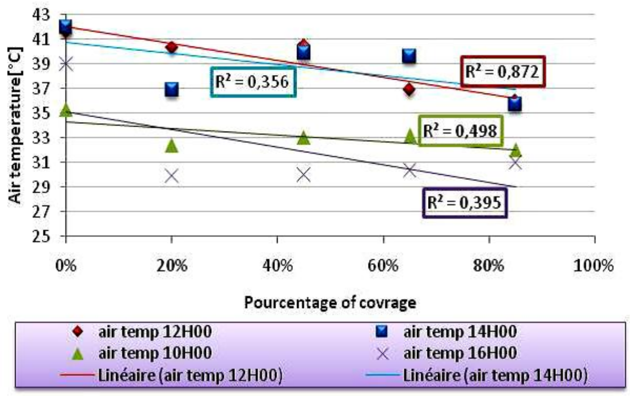

Figure 8: AverageAir temperature at the various stations of measurement during few continuous summer days

5.2. Global solar radiation

Solar radiation affects on human thermal balance which is particularly dominant outside. The quantity of global solar radiation measured at 12:00 was approximately 1707 W/m² in sunshine and between 79 W/m² and 260 W/m² under tree coverage during the experimental period. The difference in global solar radiation between the open space and the dense vegetal areas can thus reach approximately 1600 W/m² during the summer period at 12:00.

From figure 9, we can deduce that mean of global solar radiation measured at 1.5 m at the five stations of measurement during the summer period at 12:00 has a negative correlation (R^2= 0.969) with percentage of tree coverage. Dense coverage minimises direct solar radiation transmitted and increases the amount of shade. Regardless of air temperature, the quantity of solar radiation received contributes to the human heat balance: humans feel warmer in sunshine than in shade. Thus, high percentage of tree coverage can create more comfortable thermal conditions because of its effects on global solar radiation. These results are demonstrated with same coherence with another site by the same author [37]

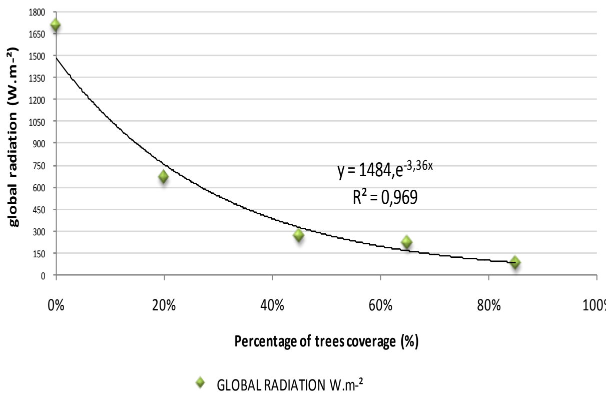

Figure 9: Global solar radiation and tree cover correlation

Another aims of this research were to examine the correlation between global irradiation received in each station of measurement and their respective local air temperatures at 12:00. Results reveal a similar comportment of global irradiation and air temperature (see figure 10). In dense urban environments with hot-dry climates, air temperature during hottest periods is thus related to the vegetation cover. However, other design parameters can be introduced for involving evaluation of air temperature, as, for example, the presence of a fountain at station 4, which is characterized by a lower air temperature than station 3.

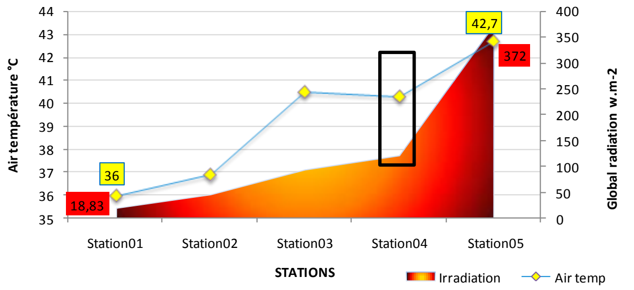

Figure10: Relationship between air temperature and quantity of irradiation at 12:00

5.3. Air Relative Humidity

From figure 11, study results as in the case of insulated space without trees (station 5) indicated lower relative humidity than covered spaces with trees, which is consistent with previous results from the literature. This result demonstrates the role of evapo-transpiration of trees. One important conclusion from measurements that a positive correlation between air relative humidity and degree of coverage (air relative humidity is higher when the percentage of tree coverage is higher).

Measurements show a difference of 6 % in relative humidity at 10:00 and at 18:00 between station 1 (densely covered with trees) and station 5 (open space). Compared with air temperature or global solar radiation, air relative humidity is relatively constant throughout the day. Vegetation thus provides great potential for the humidification of outdoor urban spaces located in dense or enclosed areas in a hot-dry climate. Additionally, note that during most of daytime, station 4, which has the water fountain and only 20 % of tree coverage, has lowered relative humidity value than stations 2 and 3, which present a more dense vegetal coverage but with no fountain.

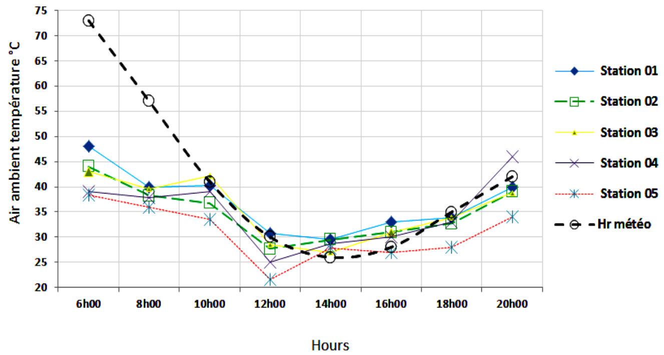

Figure 11: Air relative humidity at the measurement stations during a typical summer day.

5.4. Wind speed

The majority of measurements were taken under conditions with value of wind speed less than 1.0 m/s, which is typical of dense urban environments without high-rise buildings. Given the dense urban context of the studied site and the meteorological conditions during the monitoring, the differences in wind speed amongst the five stations are very low and do not allow us to draw conclusions about the effect of vegetation cover on wind speed sin urban public spaces.

5.5. Luminance and SVF

Daylight has a major impact on physical performance and visual comfort in open spaces. From a visual point of view, table 2 presents effect of tree coverage on the sky view factor (SVF) at the five selected stations in the square. In addition, the measurement of luminance values in the visual field which is indicative for visual perception of the spaces' users because it provides information on quality of reflected light as perceived by pedestrians. These measurements were done using a luminance meter. The investigation shows that insulated open space, which presents a higher SVF, is also characterised by higher luminance values than shaded spaces (see Figure12), due to reflected solar radiation from the surfaces of the ground (concrete) and white walls. This result confirms a close relationship between SVF and the risk of glare for this climate likely, effect of vegetation in attenuation of solar radiation and the protection against glare felt by the individuals located under tree canopy.

Table 2

Sky view factor (SVF) related to the percentage of tree coverage

Station	Fish-eye photo (vertical axis)	Fish-eye photo (horizontal axis)
Station 1 Dense tree cover Percentage of tree cover = **85 %** SVF = **0.10**		 
Station 2 Medium tree cover Percentage of tree cover = **65 %** SVF = **0.35**		
Station 3 Low tree cover Percentage of tree cover = **45 %** SVF **= 0.50**		 
Station 4 Very low tree cover and presence of a water fountain Percentage of tree cover = **20 %** SVF = **0.75**		
Station 5 No vegetation Percentage of tree cover = **0 %** SVF = **0.95**		

The value of highest luminosity was recorded at station 5, which is an insulated open space with no tree coverage (SVF = 0.95 and average albedo = 0.30) and with a high value of luminance (15 430 cd/m ² at 12:00) according to reflected light on urban materials and direct light in the visual field. The lowest luminosity value was recorded in station 1, which is the area with the most dense tree coverage (SVF=0,1and albedo value =0.1) and with the lowest value of luminance (204 cd/m² at 12:00). To reduce glare, it is recommended that luminance values remain lower than 1500cd/m² in the visual field [38], meaning that the SVF of these areas should remain lower or equal to 0.4, which corresponds to a tree coverage of at least 55 % of the space.

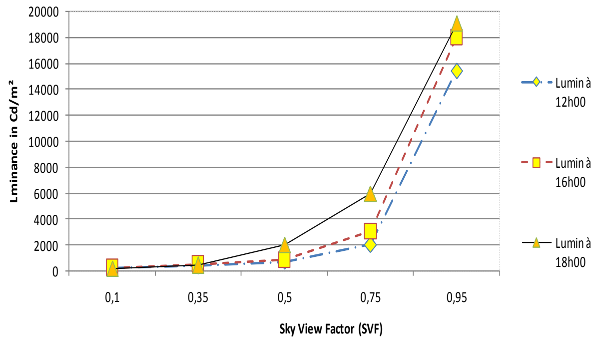

Figure12: Relationship between the luminance and the sky view factor (SVF) at the measurement stations.

5.6. Comfort index (PET)

Physiology Equivalent Temperature (PET) is selected as an outdoor thermal comfort index to evaluate quantitatively the pedestrian comfort in summer. PET, which is based on the human energy balance, it takes into account solar radiation, air temperature, air humidity, wind velocity and mean radiant temperature of the surrounding environment Tmrt [39]. Figure 13 gives the PET values at the different stations for a typical summer day and the thermal sensations associated. The highest values of the PET were recorded at station 5, which is the open space with no tree coverage, and correspond to an extremely hot sensation in the meantime [10:00 and 18:00] in this place. The lowest values of PET were recorded at station 1, which is an area with most dense tree coverage, and correspond to a lightly hot station (31.2 °C at 12:00 and 31.3 °C at 14:00).

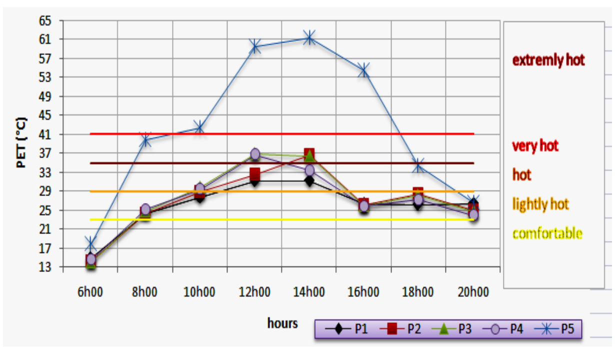

Figure13: Physiology Equivalent Temperature (PET) at the measurement stations and thermal sensations levels.

The difference in terms of PET values between stations1 and 5 with various coverage stations varies between 2 °C and 5.4 °C (at 14:00), which means a significant comfort improvement in areas shaded by trees. Results note that there is a correlation between the PET values and the percentage of tree cover (Figure 14).

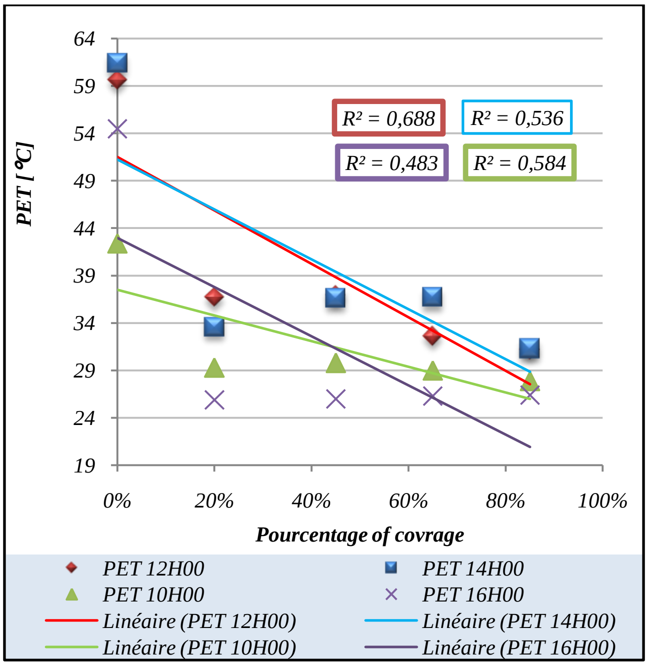

Figure14. PET and tree cover correlation.

5.7. Survey results

To compare the survey results presented below on the users' perception with the quantitative measurements, table 3 presents value variations of air temperature at different stations, and figure 15 shows the appreciation of space related to thermal sensation from questionnaire survey results with and without tree cover during this typical summer day.

The questionnaire survey results indicated that a majority (70 %) of the users located under tree coverage felt a neutral thermal sensation during the morning (at 6:00, 8:00 and 10:00), whereas 50 % of the people located in insulated open space with full solar radiation felt a hot sensation at the same time, which means a comfort improvement in areas shaded by trees.

Table 3

Sky view factor (SVF) related to the percentage of tree coverage

Air Temperature [°C]		Morning			Midday			After midday	
		6:00	8:00	10:00	11.5	14:00	16:00	18:00	20:00
Users under tree cover	Station 1	20	29.1	32	36	35.7	31	31	29
	Station 2	19.5	28.8	33.2	36.9	39.6	30.4	32.5	30
Users under low tree cover	Station 4	18.7	29.5	32.4	40.3	36.9	29.9	32	29
Users under no covered space	Station 5	18.1	28.7	35.3	**41.7**	**42**	39	36.9	31.6

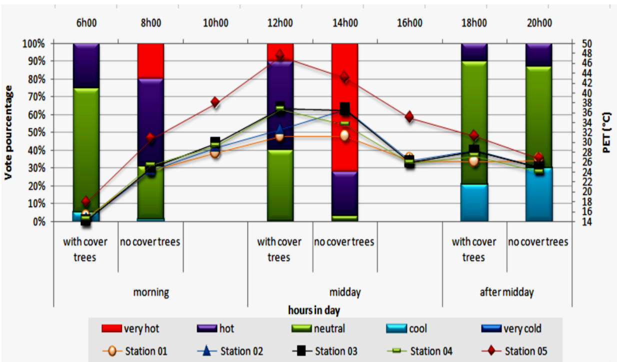

Figure15: Space appreciation related to thermal sensation from survey results and PET comfort index with and without tree cover during a typical summer day

At midday (12:00 and 14:00) in the non-covered space, the users felt uncomfortable (see figure 12 and table 3): note the high temperature values (42.7 °C), the feeling of a very hot sensation for 73 % interviewees and the feeling of a hot sensation for 24 % interviewees. Even if the situation remains hot at midday under tree canopy, appreciation of comfort rises, with only 10 % of the people voting for a very hot sensation, 50 % for a hot sensation and 40 % for a neutral sensation.

During late afternoon and evening (at 16:00, 18:00 and 20h00), the majority of participants felt a neutral thermal sensation in all the areas (see figure 12). This neutral appreciation was given by 68 % interviewees located under tree cover and by 57 % people located in the open space without trees. Note also that 10 % more interviewees chose the cool sensation in the open space, even if this area without trees was characterised by increased air temperature values (see table 3), perhaps comparing it with the extreme heat at midday in this place. From the survey, we can also observe that the feeling of well-being and comfort dominates in the vegetal areas of the square.

Global evaluation of the environment is also particularly positive there. The microclimate is considered pleasant due to shade and the soft daylight of the space. However, in station where there is no tree cover, the feelings of discomfort, heat and glare are marked, and the overall assessment of environment is negative. In the open area, the microclimate is mostly perceived as unpleasant which has relation to the strong direct solar radiation intensity and the heat released from the ground and frontages. Moreover, it appears that the factors that are most often cited as the reason for discomfort are generally strong sunshine for 45 % interviewees and high temperature for 30 % (see figure16). Other users mentioned the lack of urban furniture, the absence of trees in the open area or hot wind.

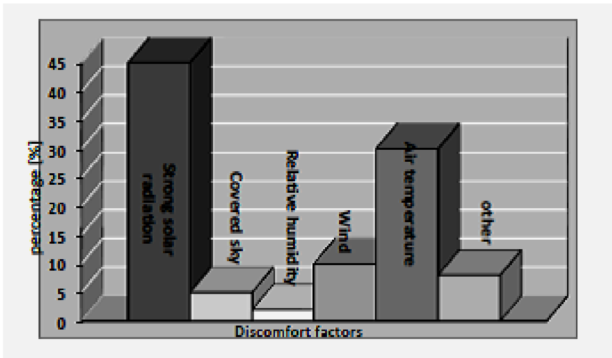

Figure16: Principal Factors contributing to discomfort of the interviewees according to their vote percentages and tree cover correlation.

Figure 17 shows the people's appreciation to sun (solar radiation) in different stations (with and without tree cover). Solar radiation that falls directly on a person significantly affects his/her perception of thermal and visual comfort. Survey results show that with tree coverage, the sun's radiation is perceived as neutral by 75 % to 100 % interviewees, whereas with no tree cover, 60 % to 90 % believe that there is too much sun. Moreover, this appreciation seems related to how using external areas in public spaces, as there are more people in the vegetal areas. In the square, stays station occupied used is station 1, which is the dense covered area with trees. The area that is least used is station 5, which has no tree coverage.

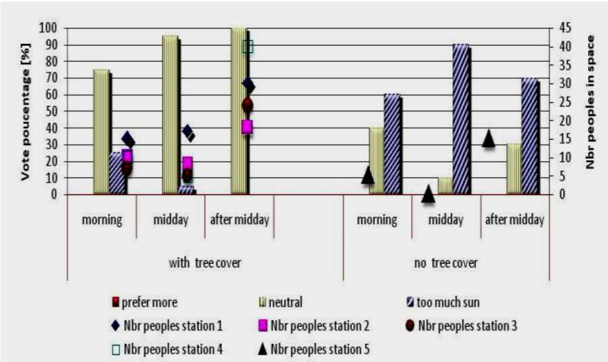

Figure17: Appreciation of the sun with and without tree cover

Finally, the survey shows that global solar radiation is the first climatic element can evaluate the degree of outdoors thermal and visual comfort in hot and dry climate. Vegetated areas are used more frequently and are perceived more comfortable than the open area without trees.

6. Conclusion

In a hot-dry climate, vegetation zones play a significant role in the city by their effects on human comfort and their regulation of microclimates. The benefits of vegetation in this climate are the reduction of incoming solar radiation and value of air temperature explained by their shading effect and evapo-transpiration. Outdoor comfort in public spaces must be studied with two approaches, quantitative and qualitative criteria and methods. The methodology used in this article the combination of in-situ quantitative thermal and visual measurements and qualitative comfort surveys.

The following conclusions confirm the results of this study. In the context of a hot and dry climate, the correlation between percentage of tree coverage and incoming global solar radiation at the pedestrian level in public spaces, which affects the pedestrians' visual and thermal comfort. We note that a relationship between the presence of trees and use of these outdoor recreational areas. Moreover, the percentage of tree coverage of a space proved to be an important metric to assess outdoor comfort in hot and dry climate. Accordingly, we concluded that with denser tree cover, we note the lower air temperature and solar radiation, the higher air relative humidity, and the better for pedestrians' thermal and visual comfort.

Indeed, in hot and dry climate, trees provide, under their canopies, significant improvements of the thermal conditions during the midday and early of afternoon, the overheated time of the day. Trees also increase quality of public spaces by their influence on daylight and the visual environment, limiting glare. Thus, increasing tree coverage in urban public spaces is an important design goal to improve pedestrians' comfort and the use of outdoor recreational areas in hot-dry climates.

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