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Evaluating the behaviour of different thermal indices by investigating various outdoor urban environments in the hot dry city of Damascus, Syria

Moohammed Wasim Yahia · Erik Johansson

Abstract Consideration of urban microclimate and thermal comfort is an absolute neccessity in urban development, and a set of guidelines for every type of climate must be elaborated. However, to develop guidelines, thermal comfort ranges need to be defined. The aim of this study was to evaluate the behaviour of different thermal indices by investigating different thermal environments in Damascus during summer and winter. A second aim was to define the lower and upper limits of the thermal comfort range for some of these indices. The study was based on comprehensive micrometeorological measurements combined with questionnaires. It was found that the thermal conditions of different outdoor environments vary considerably. In general, Old Damascus, with its deep canyons, is more comfortable in summer than modern Damascus where there is a lack of shade. Conversely, residential areas and parks in modern Damascus are more comfortable in winter due to more solar access. The neutral temperatures of both the physiologically equivalent temperature (PET) and the outdoor standard effective temperature (OUT_SET*) were found to be lower in summer than in winter. At 80 % acceptability, the study defined the lower comfort limit in winter to 21.0 °C and the upper limit in summer to 31.3 °C for PET. For OUT_SET*, the corresponding lower and upper limits were 27.6 °C and 31.3 °C respectively. OUT_SET* showed a better correlation with the thermal sensation votes than PET. The study also highlighted the influence of culture and traditions on people's clothing as well as the influence of air conditioning on physical adaptation.

Keywords Damascus · Microclimate · Thermal comfort · Thermal indices · Thermal sensation · Urban design

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Introduction

Due to the complexity of urban microclimates, and thus of determining thermal comfort in outdoor urban spaces, it is very necessary to deepen our knowledge about these issues. Such knowledge can help us to create useful and realistic guidelines for urban planning and design processes. The physical and climatic aspects of urban spaces must be improved in order to make it possible to animate underused parts of a city, and to enhance the quality of life by achieving a level of harmony between the microclimate and urban spaces.

Many previous studies have focussed on thermal comfort in outdoor urban spaces and behaviour in public spaces. Some studies examined behaviour, use of place and spatial variation (e.g. Nikolopoulou et al. 2001; Zacharias et al. 2001). Others have focussed on thermal conditions and patterns of different behaviour in urban parks (e.g. Thorsson et al. 2004). Still others have focussed on the cultural and climatic characteristics that influence the usage of outdoor urban spaces (e.g. Knez and Thorsson 2006). While these studies have provided extremely useful insights for urban designers, to put these insights into practice, reliable and relevant methods are needed for gathering information about the urban microclimate and how it is affected by existing urban design.

The outdoor thermal sensation range is wider than that indoors, spanning from thermal comfort to a stressful environment (Spagnolo and de Dear 2003; Emmanuel 2005). Moreover, outdoor conditions show large temporal and spatial variations, and the thermal balance of the body is seldom in steady state, as it is in controlled indoor environments. This situation is especially true for hot dry climates such as that in Damascus, where the large temperature variation between summer and winter as well as night and day makes adaption to the climate difficult.

Several studies related to microclimate and outdoor thermal comfort have been conducted in hot dry climates, and most of these have provided new insights to improve the outdoor thermal environment. Quite a few studies have focused on microclimate and thermal comfort in street canyons based on simulations (e.g. Ali-Toudert and Mayer 2006; Fahmy et al. 2010), measurements (e.g. Ali-Toudert et al. 2005; Johansson 2006; Bourbia and Boucheriba 2010; Shashua-Bar et al. 2011) and a physical open air scale model (e.g. Pearlmutter et al. 2007). There are, on the other hand, very few studies on subjective thermal sensation in hot dry climates. Al Jawabra and Nikolopoulou (2009) studied the outdoor thermal comfort and the effect of socio-economic background and cultural differences in the hot dry climate of Marrakech in North Africa and Phoenix in North America. The authors aimed to develop a better understanding of the complex relationship between microclimate and human behaviour in outdoor urban spaces in a hot arid climate. Micrometeorological measurements and questionnaire surveys were carried out in two sites in Marrakech and three in Phoenix. The authors argued that, particularly in the summer, the number of people and activities outdoors are influenced by the solar radiation. And people from different social backgrounds in hot arid climates have different approaches to the use of outdoor spaces. The study also concluded that the design is an important tool that can significantly improve microclimatic conditions in the specific climatic context. However, the study only calculated the predicted mean vote (PMV) index and did not investigate the behaviour of other thermal indices. In addition, the study did not calculate the thermal comfort limits and neutral temperatures. Mahmoud (2011) investigated the microclimate and thermal sensation in an urban park in Cairo, Egypt during the hot and the cold seasons. The study was based on field measurements and a questionnaire survey. By using the physiologically equivalent temperature (PET) index, the study showed an alteration in human comfort sensation between different landscape zones and it argued that most of the landscape zones in the study are thermally comfortable within a range of 22–30 °C PET in the hot month studied (June) and within 21–29 °C PET in the cold month studied (December). However, this study included only one thermal comfort index and did not include built-up areas. Moreover, the study was not conducted during the hottest and coldest months. In addition, the study did not reflect the people's thermal adaptation during the hot and cold seasons. There is thus a need for further studies in hot dry climates that take the extreme summer and winter seasons into account in different urban design patterns.

This study therefore focuses on the hottest summer and coldest winter conditions in the hot dry city of Damascus, Syria. The main aim of this study was to evaluate the behaviour of different thermal comfort indices by investigating different thermal environments and assessing people's thermal sensation in Damascus during the summer and winter seasons. This includes finding the lower and upper limits of the thermal comfort range as well as the neutral temperatures for some of these indices in the climate of Damascus. Such thermal comfort limits will help architects and urban designers to create design proposals according to the climatic needs. In addition, the novelty of this study is to examine the effect of air conditioning devices on people's outdoor thermal acceptability. This study also intends to investigate behavioural adaptation to the local climate conditions. The study is based on comprehensive micrometeorological measurements combined with a questionnaire survey during summer and winter. This study is one of few studies which deal with microclimate and subjective thermal comfort in the Middle East and the first of its kind in Damascus.

The city of Damascus

Damascus city is located in the south-west of the Syrian Arab Republic in the Middle East (Elevation: 620 m, latitude: 33.5° N, longitude: 36.5° E; Fig. 1a). The city has two main parts:
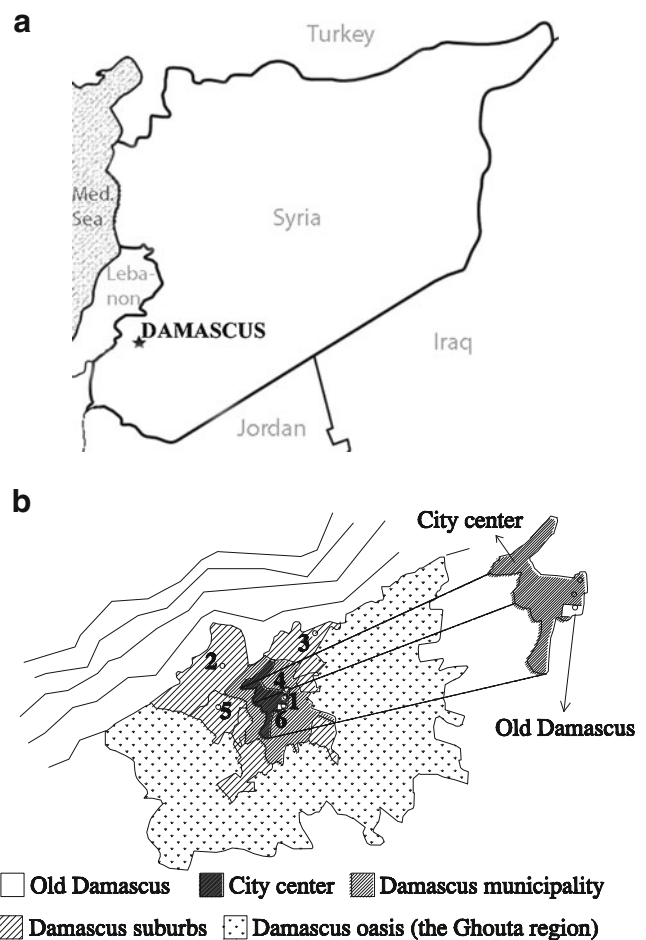

Fig. 1 a Location of Damascus in Syria, and b location of the measurement sites on a simplified map of the city of Damascus which is located between the Kassioun mountain chain in the northwest and an oasis in the south (see Fig. 3 for description of the sites)

1   The old part: It has a regular planning in general, with streets oriented N–S and E–W. Most streets are narrow in the form of deep canyons. The typical style of architecture in Old Damascus is simple outside and rich with decoration and furnishings inside, with inward orientation to the courtyards.

2   The modern part: The approach to urban design changed radically during the French colonial period (1920–45). New areas were built with wide streets in a grid pattern and buildings were outwardly oriented (Al-Kodmany 1999). Damascus is surrounded by an oasis—the Ghouta region—watered by the Barada River that used to provide the city with drinking water.

Materials and methods

A combination of measurements and structured interviews was used for assessing different thermal environments to simultaneously determine users' thermal sensation through investigating different thermal indices.

Climate in Damascus

Climatic data for temperature and relative humidity in Damascus is shown in Fig. 2. Damascus has hot sunny summers and mild winters. Summer temperatures can exceed 35 °C during the day, but evenings are generally cool. Spring and autumn are most comfortable with average temperatures in the range of 16 to 20 °C. Winters are fairly cold and temperatures can reach 0 °C at night.

Selection of measurement locations and time-periods

The locations selected were divided into three categories: two types of residential areas and parks. These three categories represent the most common environments in Damascus. The first category—residential areas in modern

Fig. 2 Temperature and relative humidity in Damascus (average values for the period 1961–1990). Source: Damascus airport meteorological station

Damascus—contained three measurement locations: Al Gassany area (circle 1 in Fig. 1b), the New Dummar area (circle 2 in Fig. 1b) and the Barzza area (circle 3 in Fig. 1b). The second category—Old Damascus—contained a deep canyon: Al Qaymarieh Street (circle 6 in Fig. 1b). The third category—parks in modern Damascus—contained two locations: Al Tigara Park (circle 4 in Fig. 1b), and Al Mazza Park (circle 5 in Fig. 1b). The measurement sites are also shown in Fig. 3.

The investigation was carried out during the hottest and coldest seasons; during August and September 2009 for the summer, and during January and February 2010 for the winter. Northwest–southeast (NW–SE), northeast–southwest (NE–SW), and east–west (E–W) street orientations were included in the measurements as well as open spaces in parks. In all six locations, the fieldwork was scheduled mainly during the 3-h period starting from around noon since this time is the hottest time of the day. However, in order to extend the study of thermal comfort—to get a greater variety in microclimatic conditions—measurements were also carried out in the morning in the Barzza area and in the evening in old Damascus (Table 1).

The official climatic data in Damascus during the measurement periods are shown in Table 2. It can be seen that the measurement days during summer were all similar to a normal day in August (see Fig. 2) whereas in winter, the weather varied considerably.

Micrometeorological measurements

The measurement equipment was placed at points where people could be expected to sit or walk. Air temperature (T_a), globe temperature (T_g), relative humidity (RH), wind speed (W) and wind direction (W_d) were measured. The measured microclimatic variables, measurement instruments, and their accuracy are presented in Table 3. The measurements in Al Gassany area, the Barzza area, and Al Mazza park were conducted mainly in sunshine, whereas in Al Tigara park and the Al Gassany area, measurements were conducted partly in shade. Furthermore, the measurements in Old Damascus were completely in shade due to the high aspect ratio. Three areas—Al Gassany area, Old Damascus, and Al Mazza park—which represent the three studied categories of urban environments in Damascus, were studied more in detail. Figure 4 shows the urban characteristics of these three areas.

For all measurements except wind, the height of the equipment was 1.1 m, which corresponds to the average height of the centre of gravity for adults (Mayer and Höppe 1987). The wind speed was measured at a height of 2 m, but it was later extrapolated down to 1.1 m using the following formula:
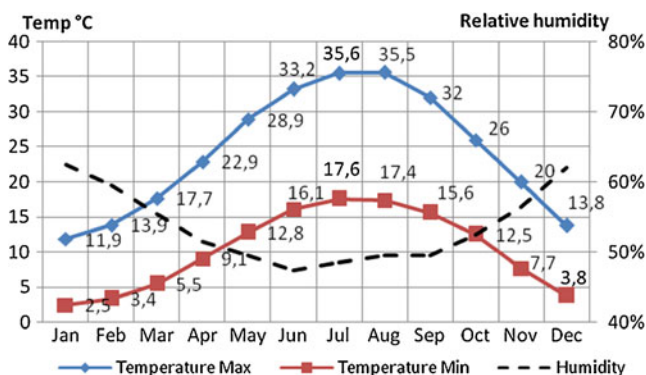
$$W_{1.1} = W_{2.0} \times (1.1/2.0)^{0.25} \qquad (1)$$

Fig. 3 a–f Measurement sites in the city of Damascus. a Al Tigara park, b Al Gassany area, c New Dummar area, d Barzza area, e Al Mazza park, f Old Damascus

Where $W_{1.1}$ = wind speed at the height of 1.1 m, and $W_{2.0}$ = wind speed at the height of 2 m.

The mean radiant temperature (MRT), which considers both short-wave and long-wave radiation and represents the weighted average temperature of an imaginary enclosure that gives the same radiation as the complex urban environment, has the strongest influence on thermophysiological significant indices such as the physiological equivalent temperature (PET) and the predicted mean vote (PMV) (Matzarakis et al. 2007). In this study, MRT was derived from the globe temperature and the wind speed using the following formula (Thorsson et al. 2007):

$$MRT = \left[(T_g + 273.15)^4 + \frac{1.335 \times 10^8 W^{0.71}}{\varepsilon D^{0.4}} \times (T_g - T_a) \right]^{\frac{1}{4}} - 273.15$$

(2)

Table 1 Orientation and land use of the measurement locations as well as date and time of measurements

Category	Location name	Orientation	Land use	Date of measurements	Time of measurements
Modern Damascus	Al Gassany	NW–SE	Residential road	13 August 2009	13:00 to 15:00
				10 January 2010	12:15 to 15:25
	New Dummar	–	Residential space	15 August 2009	12:40 to 14:40
				24 January 2010	12:35 to 14:30
	Barzza	NE–SW	Residential and commercial space	18 August 2009	13:20 to 15:00
				26 September 2009	08:50 to 11:35
				31 January 2010	11:55 to 14:35
				6 February 2010	08:00 to 11:11
Old Damascus	Al Qaymarieh street	E–W	Residential, commercial and recreational road	19 August 2009	12:30 to 14:20
				30 September 2009	15:30 to18:15
				6 February 2010	12:10 to 15:10
				5 February 2010	16:30 to 18:30
Public parks	Al Tigara Park	–	Recreational space	12 August 2009	13:00 to 14:40
				17 January 2010	11:45 to 15:05
	Al Mazza Park	–	Recreational space	17 August 2009	12:50 to 15:00
				5 February 2010	11:50 to 15:10

Where T_g = globe temperature (°C), W = air velocity (m s^{-1}), T_a = air temperature (°C), D = globe diameter=40 mm, and ε= globe emissivity=0.97.

The globe thermometer consisted of a table tennis ball painted flat grey. It should be noted that the MRT calculated in this way is very sensitive to variations in wind speed, e.g. an increase in wind speed will mean that the globe cools down and T_g decreases, but as this cooling will not be instantaneous due to the thermal inertia of the globe, MRT will be overestimated. Similarly, a sudden decrease in wind speed will lead to an underestimated MRT. To reduce the

sensitivity to wind speed variations, 10 min averages of wind speed were used in calculations of MRT.

Calculation of outdoor thermal comfort indices

A great number of indices that try to predict the state of thermal comfort, mainly for indoor applications but also for outdoors, have been developed. The PMV, standard effective temperature (SET*) and the new effective temperature (ET*) were all developed for indoor applications (McIntyre 1980). In addition, many indices have been designed

Table 2 Official climatic data for the period of the fieldwork in summer and winter (air temperature, relative humidity, and wind speed). Source: Damascus airport meteorological station

Date	Maximum air temp. (°C)	Minimum air temp. (°C)	Relative humidity (average) (%)	Wind speed (average) (m/s)
12 August[a]	37.0	17.3	33	3.2
13 August[a]	37.4	18.0	33	4.1
15 August[a]	38.2	19.8	38	4.4
17 August[a]	39.4	20.0	31	5.4
18 August[a]	39.6	19.0	37	5.4
19 August[a]	37.8	20.0	40	5.1
10 January[b]	20.2	2.0	47	1.5
17 January[b]	19.7	7.0	54	4.0
24 January[b]	14.0	4.8	84	6.4
31 January[b]	19.5	5.6	67	4.0
5 February[b]	9.5	0.0	45	4.7
6 February[b]	9.8	−5.0	53	1.2

[a]Measurement days during the summer time (August 2009) for the six studied locations.

[b]Measurement days during the winter time (January and February 2010) for the six studied locations

Table 3 Measured variables, instruments, and accuracy of the instruments. T_a Air temperature, T_g globe temperature, RH relative humidity, W wind speed, W_d wind direction

Variable	Instrument	Accuracy
T_a	Rotronic hydroclip S3	±0.3 %°C
T_g	Pt100 in a grey plastic ball	±0.3 °C at 0 °C
RH	Rotronic hydroclip S3	±1.5 % RH
W, W_d	Gill windsonic anemometer	±2 %@12 m/s

primarily for outdoor applications, e.g. the perceived temperature (PT), which is based on the comfort equation of Fanger (Jendritzky et al. 2000), OUT_SET*, which is an adaptation of SET* for outdoor use (Pickup and de Dear 2000), and the PET (Höppe 1999). In this study, PET, OUT_SET*, ET*, and PMV were used to assess and evaluate the outdoor thermal environment in Damascus, whereas only PET and OUT_SET* were used for further analysis of thermal comfort limits. The RayMan PC Model (Matzarakis et al. 2007) was used to calculate PET, whereas

Fig. 4 Urban characteristics and measurement spots in **a** Al Gassany area, **b** Old Damascus and **c** Al Mazza park

the ASHRAE Thermal Comfort Program (Fountain and Huizenga 1994) was used to calculate the OUT_SET*, ET*, and PMV indices.

Structured interviews

A questionnaire survey was performed at the same time as the measurements in each location in order to compare the actual thermal sensation with the calculated thermal indices derived from the micrometeorological measurements. A structured interview form was designed to assess the people's thermal sensation and other parameters such as gender and age, clothing, reason for being in the places, time spent outdoors, thermal preference, assessment of the microclimate, aesthetic qualities of the place, emotional state, and assessing the attitude to urban outdoor exposure. However, this paper discusses mainly results pertaining to thermal comfort sensation, activity and clothing. The structured interview forms were not answered by people individually but by support from an assistant group belonging to Damascus University. Each interview took an average of 5 min to complete. A total of 920 people in both summer and winter were interviewed by a random selection. In each season, there were 60 interviews in each location plus 50 interviews in the Barzza area in the morning and in Old Damascus in the evening. The majority of the interviewees were between 20 and 65 years of age. Of the total sample 76 % were male and 24 % female. This percentage, which is similar in all areas in both seasons, reflects the fact that fewer women than men are present in public space for cultural reasons. The subjects were asked to report their thermal sensation according to a 9-point scale: very cold (−4), cold (−3), cool (−2), slightly cool (−1), comfortable (0), slightly warm (+1), warm (+2), hot (+3) and very hot (+4).

Assessment of neutral temperatures and thermal comfort range

To determine the neutral temperature, which is defined as the temperature at which people feel thermally neutral (neither cool nor warm) and which corresponds to the value zero in the thermal sensation scale, probit technique (Ballantyne et al. 1977) was used. The neutral temperatures were determined by grouping all thermal sensation votes (TSV) <0 into a group of cooler than neutral, and all votes TSV >0 into a group of warmer than neutral. The votes TSV=0 were split randomly between the groups TSV <0 and TSV >0. The neutral temperature was then determined as the index temperature at which 50 % of the sample voted cooler than neutral and 50 % voted warmer than neutral. SPSS 18 (Statistical Package for the Social Sciences Software for Windows) was used to perform the probit analysis. According to ASHRAE Standard 55 (2004), acceptable thermal conditions must be acceptable to 90 % (high standard) or 80 % (typical applications) of the users. This means that ≤10 % or ≤20 % of the users feel thermally unacceptable. Normally, votes outside the three central categories of the TSV scale are considered to be unacceptable votes (e.g. Lin 2009). In this study, the comfort limits for both 10 % and 20 % unacceptability were calculated. It should be noted that in the winter there were a few votes in the range of +3 to +4 and in the summer there were even fewer votes in the range −3 to −4. Thus, these votes were checked carefully and a few strange values were excluded from the comfort limits and neutral temperature calculations, i.e. those that voted −4 during the summer although they wanted it to be cooler, and those that voted +4 during the winter although they wanted it to be warmer.

Results

Microclimatic variations

Table 4 shows the variations of measured T_a, RH, W, and MRT in summer and winter for all locations. Table 4 illustrates the considerable differences between the seasons. However, the average values of wind speed were nearly the same (0.7 m/s in the summer and 0.8 m/s in the winter). The results also show the microclimatic differences between the old and the modern part of Damascus, especially in summer, due to completely different urban design features in terms of aspect ratios, building materials, and building geometries (Figs. 3, 4). The reason why the average values of MRT in Al Gassany area and Al Tigara park in the summer were lower than the values in other locations in modern Damascus was due to the shade from trees that affected the measurements. For both seasons, it was noticed that high values of MRT are not necessarily correlated with high values of T_a.

Figure 5 shows the spatial variations of MRT for Al Gassany area, Old Damascus, and Al Mazza park as examples representing the outdoor urban environment in Damascus. It can be seen that, in summer, MRT was higher in Al Mazza park than in Al Gassany area. The values in Old Damascus were considerably lower than in the two other places. The instability of MRT in Al Gassany area was due to the positioning of the measurements equipment, which was mounted beside a pedestrian path under a row of small trees where the globe thermometer during the measurement period was alternately in shade and sunshine. In winter, there were major differences between the studied areas in terms of MRT. This is mainly because the weather was changing from one day to another during the measurement period (Table 2) and sometimes the change of, e.g. clouds/solar exposure, even occurred during the measurements. However, as in summer, MRT is very stable in Old Damascus.

Table 4 Average values of measured air temperature (T_a), relative humidity (*RH*), wind speed (*W*), and mean radiant temperature (MRT) in summer and winter in all locations. The measurements were taken on different days in the afternoon, unless otherwise stated

Location	Average T_a (°C)		Average *RH* (%)		Average *W* (m/s)		Average MRT (°C)	
	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
Al Gassany area	34.0	19.5	20.2	30.5	0.7	0.6	59.4	34.2
Dummar area	36.3	9.7	18.9	74.2	0.7	0.8	69.8	11.7
Barzza area	36.9	9.8	18.1	73.3	0.9	0.8	71.4	13.4
Al Tigara park	30.8	15.4	31.6	46.7	0.9	0.8	58.3	28.5
Al Mazza park	37.0	6.7	18.1	42.4	1.0	1.4	70.6	36.2
Old Damascus	34.4	8.3	24.3	35.1	0.4	0.3	36.5	9.3
Barzza area (morning)	31.1	8.0	20.5	35.8	0.5	0.4	61.6	35.2
Old Damascus (evening)	26.9	5.6	23.2	40.7	0.4	0.8	27.4	5.4
All locations average	33.4	10.4	21.8	47.3	0.7	0.8	56.9	21.7
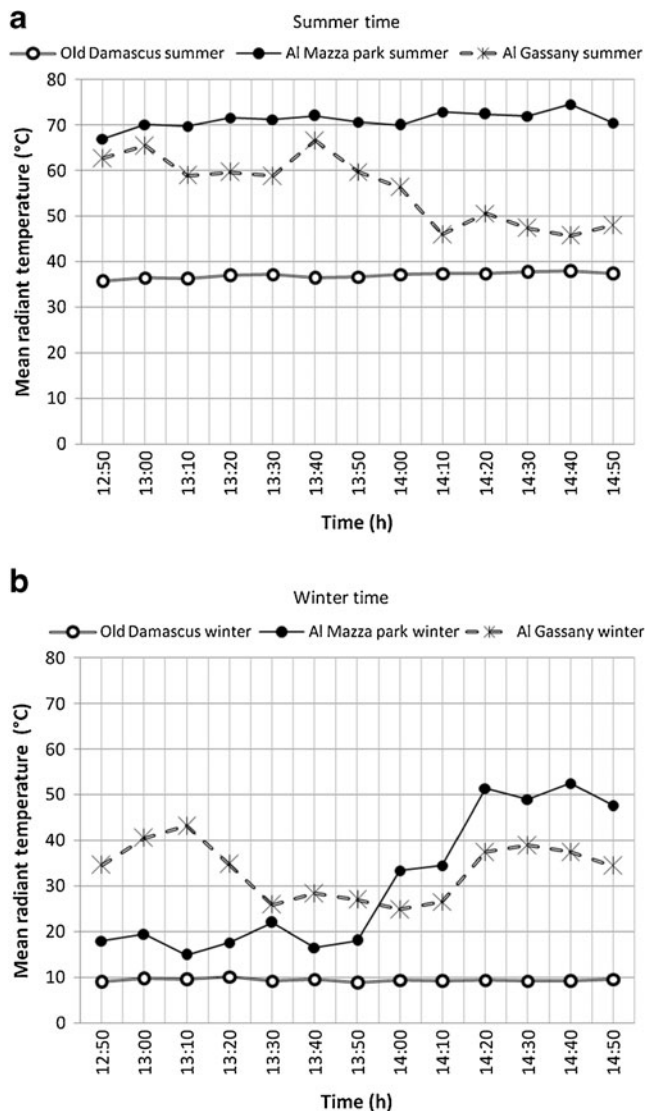
Fig. 5 Mean radiant temperature (MRT) variations in Al Gassany area, Old Damascus, and Al Mazza park during **a** summer and **b** winter

Characteristics of different thermal indices

Table 5 shows the calculated PET, OUT_SET*, ET*, and PMV for all studied locations. For all indices, the results reveal that in the summer Old Damascus is less stressful than the outdoor urban spaces in modern Damascus, whereas in winter, Old Damascus is colder than the other areas due to the lack of solar exposure as a result of the high building density. In summer, Al Gassany area and Al Tigara park, where there was some shade from trees, were less stressful than the other sites in modern Damascus where the measurement spot was exposed to sunshine all the time.

Table 5 shows that the average values of the PET index are higher in summer and lower in winter than the average values of both the OUT_SET* and ET* indices. ET*, in turn, has higher values in summer and lower in winter than OUT_-SET*. One of the reasons why PET and ET* have more extreme values is that they do not take clothing and activity into account as input variables. Another reason why OUT_-SET* is slightly lower than ET* in the summer may be because the effect of wind speed is included in the calculation of OUT_SET* and not in ET*. For the PMV index, the calculated values in winter are within the range from −3 (very cold) to +3 (very hot) except in Old Damascus in the evening. Only Al Gassany area was comfortable, i.e. within the comfort range of the index of −0.5 to +0.5 but this was mainly because the particular afternoon was exceptionally warm. In summer the values were in general well above the defined range of PMV and reached as high as 8 in the Barzza area. Only the values of Old Damascus, both during the day and in the evening, were within the defined scale of PMV.

Subjective thermal sensation

Figure 6 illustrates the clear differences between people's subjective thermal sensation in summer and winter for all

Table 5 Average calculated values in summer and winter in all locations for the physiological equivalent temperature (PET), the outdoor standard effective temperature (OUT_SET*), the new effective temperature (ET*), and the predicted mean vote (PMV). The values are from different days in the afternoon, unless otherwise stated

	Avg PET °C		Avg OUT_SET* °C		Avg ET* °C		Avg PMV	
	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
Al Gassany area	46.1	23.2	36.0	27.6	36.7	23.9	5.5	0.2
Dummar area	53.3	7.2	38.4	15.6	38.4	10.6	6.5	−2.8
Barzza area	54.0	7.8	38.2	15.8	39.3	11.2	8.0	−2.5
Al Tigara park	42.7	17.2	34.6	21.3	36.1	19.9	4.8	−1.6
Al Mazza park	53.2	11.1	37.9	19.4	39.1	15.2	7.7	−2.1
Old Damascus	35.3	6.7	32.3	14.4	31.9	8.6	2.9	−2.2
Barzza area (morning)	46.1	17.1	36.2	23.5	36.9	19.3	5.7	−1.1
Old Damascus (evening)	26.3	2.0	25.7	9.9	25.5	5.5	0.5	−3.9
All locations average	44.6	11.6	34.9	18.4	35.5	14.3	5.2	−2.0

studied locations together. The result shows that the people's thermal sensation in summer is between cool and very hot, whereas in winter it is between very cold and hot. The highest percentage of people feels comfortable in the winter time, whereas they feel hot in the summer time. The reason why the distribution of the comfort votes was spread widely in both summer and winter is due to the varying weather conditions between the measurement days (especially in winter) but also due to individual differences in people's thermal sensation. A similar difference in distribution between seasons was found in Sydney, Australia, by Spagnolo and de Dear (2003).

Fig. 6 Percentage frequencies for people's thermal sensation in the summer and winter seasons

Relationship between thermal sensation votes and thermal indices

When comparing the relationship between TSV and the calculated indices (PET and OUT_SET*) it was found that the original thermal sensation scales of these indices often do not correspond to people's actual thermal sensation in Damascus. Figure 7 shows the relationship between TSV and the index temperatures for PET and OUT_SET* for each 1 °C index temperature. For both indices, the results show in general a wide spread of votes. This reflects variations in people's thermal sensation, which is due supposedly to differences in thermal history, emotional state, etc. as well as individual thermal preferences. The variations are also caused by differences in activity and clothing. The regression lines for all the tested indices for both seasons are as follows:
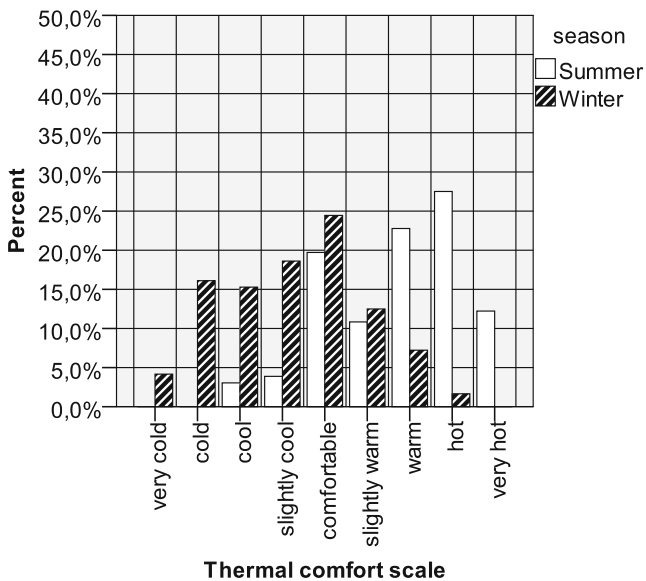
PET

$$\text{Summer} \quad \text{TSV} = 0.060 \times \text{PET} - 0.941 \quad \left(R^2 = 0.42\right) \tag{3}$$

$$\text{Winter} \quad \text{TSV} = 0.114 \times \text{PET} - 2.755 \quad \left(R^2 = 0.60\right) \tag{4}$$

OUT_SET*

$$\text{Summer} \quad \text{TSV} = 0.134 \times \text{OUT\_SET} - 3.208 \quad \left(R^2 = 0.87\right) \tag{5}$$

$$\text{Winter} \quad \text{TSV} = 0.082 \times \text{OUT\_SET} - 2.928 \quad \left(R^2 = 0.66\right) \tag{6}$$

Fig. 7 Correlation between the mean thermal sensation votes (TSV) and **a** the PET index and **b** the OUT_SET* index in summer and winter
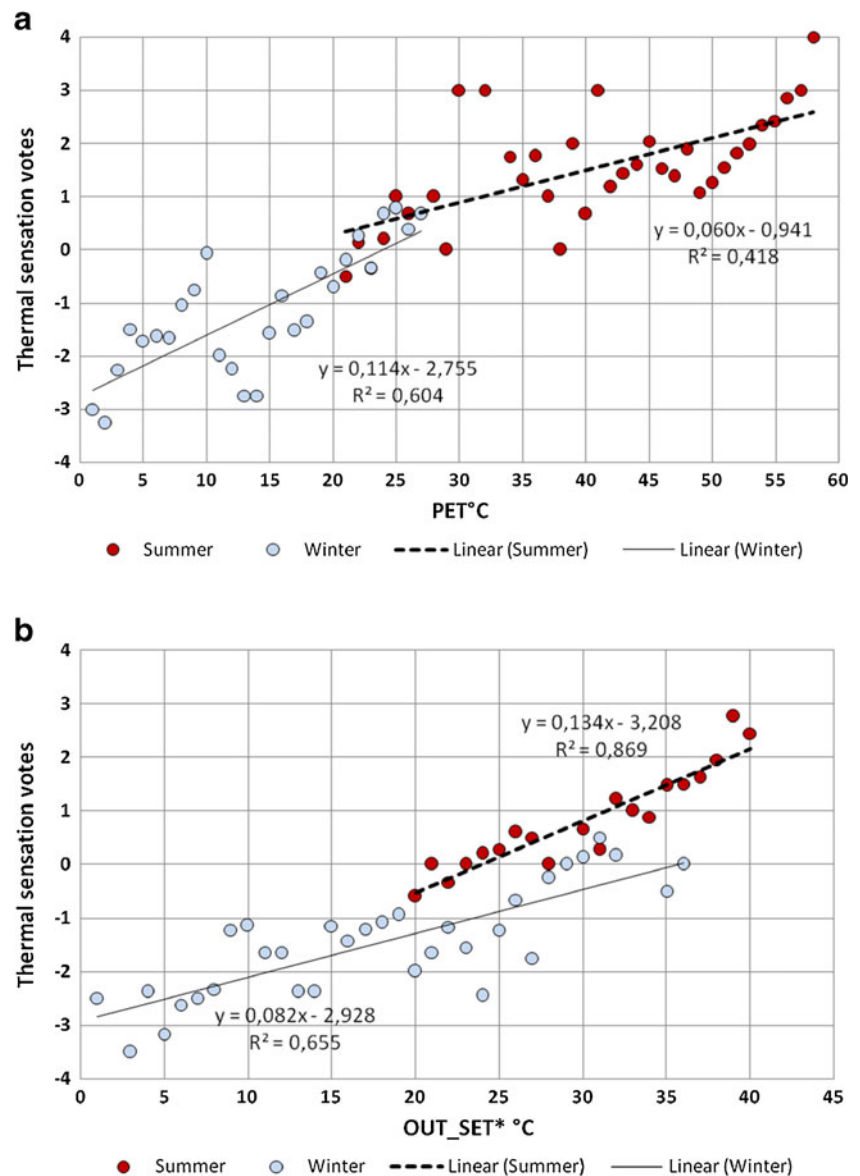

The slopes of the regression lines indicate the sensitivity to changes of the index values. In summer, for PET, the slope is 0.060, corresponding to 16.6 °C PET per actual thermal sensation unit, whereas in winter the slope is 0.114, corresponding to 8.8 °C PET per actual thermal sensation unit. This shows that people's thermal sensation is more sensitive to variations of PET in winter than in summer. A similar tendency was found by Lin (2009) in Taiwan. In the case of the OUT_SET*, the slope for the summer is 0.134, which corresponds to 7.5 °C, whereas in winter, the slope is 0.082, which corresponds to 12.2 °C per thermal sensation unit. This means that people's thermal sensation is more sensitive to variations of OUT_SET* in summer than in winter. A similar tendency was found in Taiwan by Lin et al. (2011).

The results show that the OUT_SET* index—especially in summer—has better correlation with TSV than the PET index (R^2 for OUT_SET* is about 0.7 in winter and 0.9 in

summer, whereas R^2 for PET is about 0.6 in winter and 0.4 in summer). This is because PET does not take clothing and activity into account as input data (Höppe 1999).

Thermal comfort limits and neutral temperatures

Figure 8 shows the percentage of unacceptability in summer and winter for each 1 °C index temperature of the PET and OUT_SET* indices. From the graphs in Fig. 8, the upper and lower limits of the comfort range for different percentages of unacceptability can be determined. However, to obtain a comfort range with both the lower and upper limit, measurements during all seasons including spring and/or autumn would be required, especially in a hot dry climate where there is a considerable difference between summer and winter. Since in this study the field measurements were conducted only during the extreme weather conditions of summer and winter
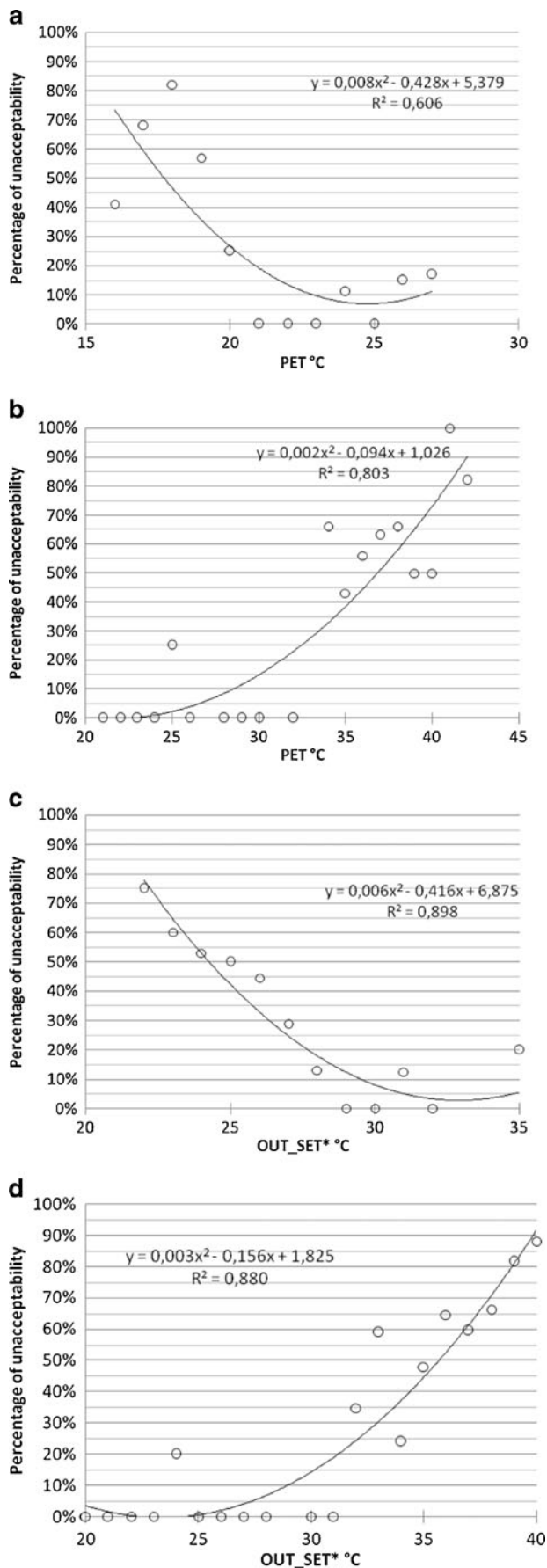
Fig. 8 Level of thermal unacceptability for **a** PET during winter, **b** PET during summer, **c** OUT_SET* during winter and **d** OUT_SET* during summer

respectively—and mainly during 3 h of the afternoon—it was not possible to define one comfort range for the whole year that is accepted by 80 % or 90 % of the people. Instead, summer and winter seasons were split up into two different groups and the upper and lower comfort limits for the summer and winter could be determined. These limits will be useful to architects and urban designers because they are valid for the most extreme weather conditions.

The results illustrate that the OUT_SET* index has a better correlation with people's thermal unacceptability than the PET index (R^2 for OUT_SET* is about 0.9 for both winter and summer, whereas R^2 for PET is about 0.6 in winter and 0.8 in summer). This can be explained by the influence of clothing and activity on people's thermal comfort.

Table 6 shows the upper and lower limits of thermal comfort range for 80 % and 90 % acceptability for PET and OUT_SET* during summer and winter in Damascus. An 80 % degree of acceptability will be applied in this study for further analysis since a wider comfort range is more appropriate outdoors due to the large climate variability (Spagnolo and de Dear 2003). Table 6 also illustrates that the neutral temperatures in summer for both PET and OUT_SET* are considerably lower than in winter.

Behavioural adjustments—the role of clothing

Table 7 shows the reported average values of activity level and clothing insulation in all areas studied during summer and winter. In general, very small differences were found between areas and seasons in terms of people's physical activity, the reason being that, during the fieldwork the people were mainly standing, walking slowly, or sitting. These actions represent the typical daily behaviour of the people in Damascus city in the outdoor urban environment both in summer and winter. On the other hand, the clothing values in summer time were significantly lower than the values in the winter due to the weather differences between these two seasons (see Table 7). The clothing levels were, however, similar within each season except during the measurements in Al Tigara Park on 17 January, which was a warm winter day (see Table 2); on this day the clothing value was clearly lower than the other winter values.

Figure 9 shows the relationship between the average clothing value and the thermal comfort indices (PET and OUT_SET*) for each 1 °C index temperature. For both indices, the results show that when the index values increase, the clothing values decrease. This result is evidence of adaptation to the weather and shows that climate conditions affect people's clothing. For these two indices, the results indicate that the

Table 6 Neutral temperatures and upper limits in summer and lower limits in winter of the comfort range at 80 % and 90 % acceptability for PET and OUT_SET* in Damascus

Index	Neutral temperatures (°C)		Comfort range limits (°C)		
	Winter	Summer	Acceptability (%)	Lower limit Winter	Upper limit Summer
PET	23.4	15.8	90	22.8	28.5
			80	21.0	31.3
OUT_SET*	35.1	23.1	90	28.9	29.1
			80	27.6	31.3

distribution of clothing values is spread more widely in winter than summer. However, the variation of clothing values for PET—between 0.5 and 1.7 clo—is smaller than OUT_SET—between 0.6 and 2.4 clo—and this is because OUT_SET* takes clothing into account as input data. Thus, OUT_SET* is more sensitive to clothing than PET.

Figure 10 shows the relationship between clothing and thermal sensation votes in summer and winter as one sample. Regardless of the thermal index, Fig. 10 shows that the distribution of clothing values—in relation to thermal sensation votes—is between 0.4 and 2.5 clo. This range represents people's average clothing values during the summer and winter seasons. Figure 10 also illustrates that when people vote within the cold side of the thermal comfort scale, they generally tend to wear heavy clothing, whereas when they vote within the warm side of the thermal comfort scale, they tend to wear light clothing. The result confirms the effect of thermal comfort on clothing.

Physiological adaptations—the effect of air conditioning

In hot dry Damascus, using indoor air conditioning devices in summer in order to provide better thermal conditions is very common. In order to investigate the effect of air conditioning on people's thermal sensation outdoors, a comparison between thermal comfort limits for people who have and those who do not have air conditioning devices—both at home and at work—has been conducted. Figure 11 shows

the relationship between the level of acceptability and the indices OUT_SET* and PET for each 1 °C index temperature. The results show that, at 80 % acceptability, the lower and upper limits of the comfort zone for people who do not have air conditioning devices (25.5 °C and 32 °C, respectively) are wider than the limits for those who have air conditioning devices (29 °C and 30.5 °C, respectively). In summer, the results illustrate that the people who do not have air conditioning devices have a greater ability to accept higher temperatures than those who have air conditioning devices, whereas in winter, they are more able to accept lower temperatures than those who have air conditioning devices. This is evidence of a physiological adaptation to the outdoor environment in Damascus city. The results agree well with the physiological adaptation found in naturally ventilated offices in Thailand when compared with offices with air conditioning (Busch 1992).

Discussion

Effect of urban geometry on microclimates

In summer, streets and parks in modern Damascus are more thermally stressful than the streets in Old Damascus. This reflects the strong influence of the urban geometry on the microclimate within built environments. Old Damascus has deep street canyons with high aspect ratios, which create a

Table 7 Reported average values of activity and clothing in all studied areas during the measurement periods for the summer and winter seasons

Location name	Activity (average) met		Clothing (average) clo	
	Summer	Winter	Summer	Winter
Al Gassany area	1.6	1.6	0.56	0.96
Dummar area	1.7	1.5	0.57	1.00
Barzza area	1.4	1.6	0.56	0.99
Al Tigara Park	1.4	1.4	0.57	0.85
Al Mazza Park	1.4	1.6	0.58	1.02
Old Damascus	1.8	1.7	0.57	1.01
Barzza area (morning)	1.4	1.6	0.54	0.94
Old Damascus (evening)	1.6	1.5	0.59	1.00
All locations average	1.5	1.6	0.57	0.97

Fig. 10 Relationship between clothing and the thermal sensation votes in summer and winter
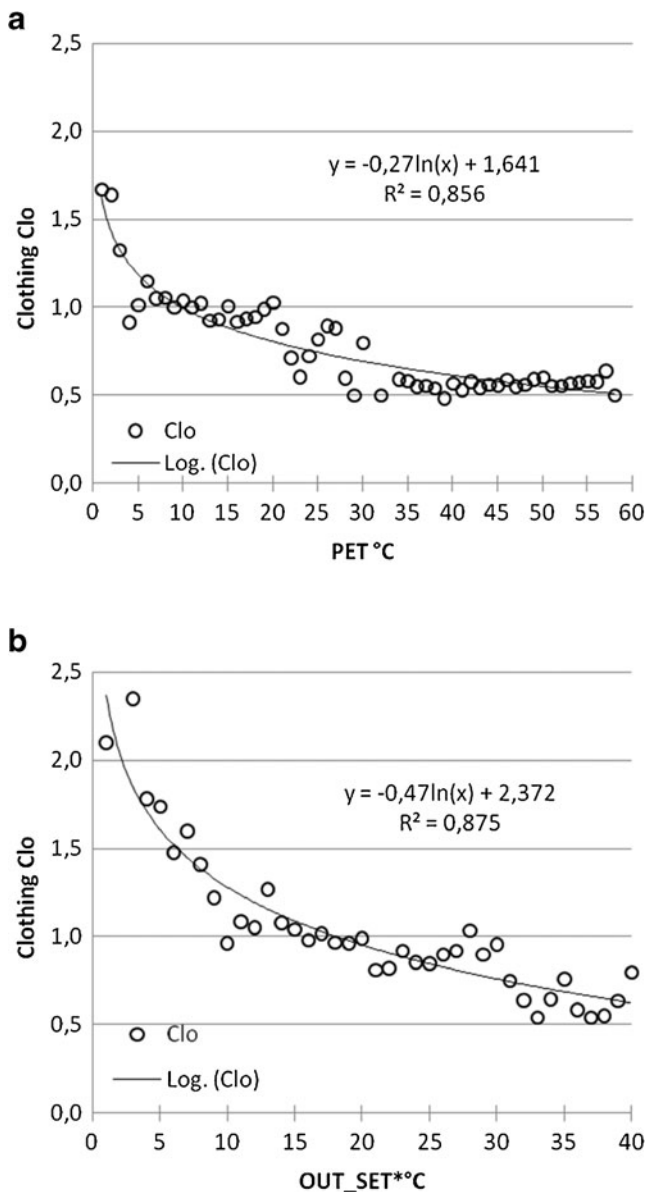

Fig. 9 Relationship between clothing and **a** the PET index and **b** the OUT_SET* index for summer and winter together

more comfortable microclimate since direct solar radiation and the mean radiant temperature decrease with the increase in aspect ratio (Ali-Toudert and Mayer 2006). In contrast, the outdoor spaces in modern Damascus have a low aspect ratio and, consequently, these spaces are more exposed to solar radiation, which has a negative impact on outdoor thermal comfort. Moreover, few locations in the studied areas of modern Damascus have been designed to protect against solar radiation, especially in the Barzza and New Dummar areas. However, in the parks and in the Al Gassany area, less stressful environments can be found due to the existence of shading trees.

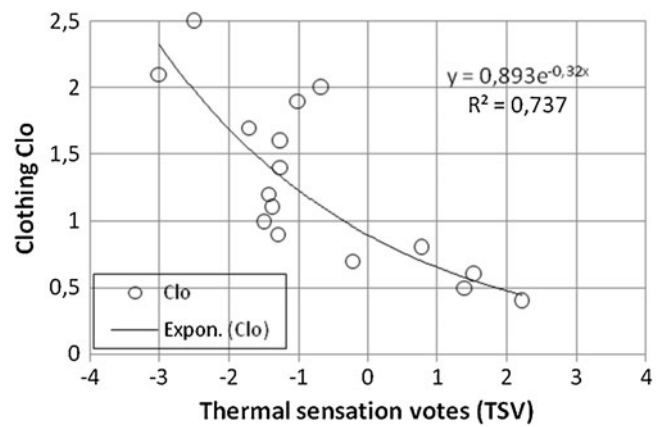In winter, it was more difficult to compare the microclimatic qualities between the areas since weather conditions varied from day to day during the field work. Old Damascus was the coldest area and that is because of the cold weather on the measurement day as well as the deep canyon, which prevents the direct solar radiation to reach the ground. In contrast, the Al Gassany area was most comfortable, because of the warm weather on the measurement day as well as the fact that the urban geometry in Al Gassany area allows the solar beam to reach the ground.

Thermal comfort zones and neutral temperatures

In this study, all the studied indices had basically the same tendency in assessing the outdoor physical urban environment in the hot dry climate of Damascus. The study of Spagnolo and de Dear (2003) found that many of the thermal comfort indices they tested were statistically better at predicting the outdoor thermal comfort in summer than in winter due to the skewed nature of the winter sample in their study. In this study, no significant difference could be found between summer and winter predictions, which may be because both the summer and winter samples were skewed and this may have affected neutral temperatures. However, the results illustrate that the OUT_SET* index has a better correlation with TSV and thermal unacceptability than the PET index, and this may be due to the role of clothing and activity that are included in OUT_SET*.

In Table 8 the calculated thermal comfort ranges and neutral temperatures of PET from this study in Damascus are compared with other studies.

It may seem surprising that the neutral temperature for Damascus in the summer is lower than in the winter (Table 8) since one would expect the local population to be adapted to the weather conditions in each season. However, our results agree with those of Spagnolo and de Dear (2003). The latter authors explained the phenomenon by applying the concept of alliesthesia, which is a psychological mechanism explaining the differences in sensation between seasons, i.e. if people feel

a

$$y = -0{,}464x^2 + 30{,}37x - 393{,}3$$
$$R^2 = 0{,}817$$

$$y = -0{,}384x^2 + 28{,}00x - 409{,}1$$
$$R^2 = 0{,}643$$

○ I don't have AC
✕ I have AC
— Poly. (I don't have AC)
--- Poly. (I have AC)

b

$$y = -0{,}357x^2 + 17{,}30x - 108{,}0$$
$$R^2 = 0{,}775$$

$$y = -0{,}370x^2 + 16{,}82x - 88{,}06$$
$$R^2 = 0{,}839$$

○ I don't have AC
✕ I have AC
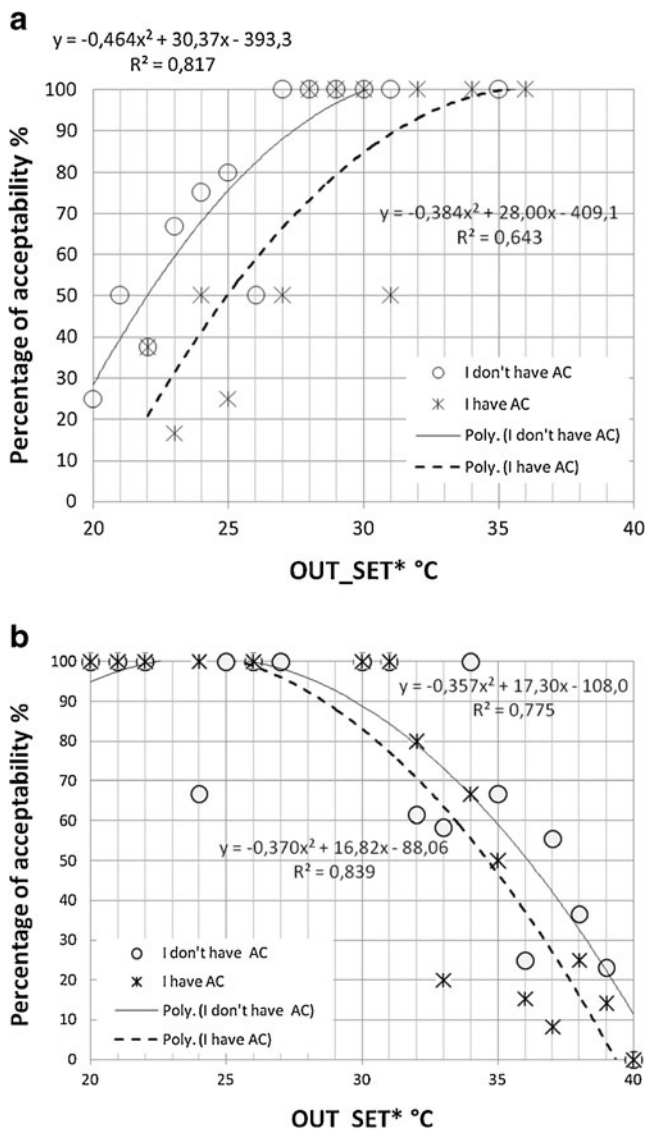— Poly. (I don't have AC)
--- Poly. (I have AC)

Fig. 11 Relationship between the level of acceptability and OUT_SET* for those who have air conditioning or not for **a** winter and **b** summer

warm, then anything which makes them feel colder will be pleasant and vice versa. Conversely, the results disagree with the results for Taiwan (Lin 2009) and Cairo (Mahmoud 2011), where the authors found slightly higher neutral temperatures in summer than in winter (see Table 8).

This study has defined different thermal comfort limits for the summer and winter, whereas other studies defined only one comfort range for the whole year. The reason for studying the seasons separately is that people adapt themselves differently to each season physiologically and psychologically (Mahmoud 2011). Thus, the lower limit for PET in winter (21 °C) is fairly close to the urban park in Cairo (22 °C), and the upper limit in summer (31 °C) is close to that in the urban park of Cairo (29 °C). One explanation for this difference might be that the study in Cairo was conducted only in a park whereas this study was conducted in different urban environments. In addition, this study found that, in summer, parks are less stressful than the built-up environments in the city (see Table 5).

Table 9 compares the calculated thermal comfort ranges and neutral temperatures of OUT_SET* with those of other studies. The winter neutral temperature in Damascus is higher than that of summer, and the difference between the summer and winter neutral temperatures is 12 °C. This agrees well with the results in subtropical Sydney (Spagnolo and de Dear 2003), where the difference was also around 12 °C. Moreover, the summer neutral temperatures in Damascus (23.1 °C) and in Sydney (23.3 °C) were almost equal. However, Lin et al. (2011) found higher neutral OUT_SET* in the hot season (29.3 °C) than in the cool season (28 °C), and the difference between these two is only 1.3 °C.

Clothing and cultural traditions

Many studies have investigated the relationship between clothing and thermal comfort. Andrade et al. (2011) concluded

Table 8 Comparison of neutral temperatures and comfort ranges of the PET index in different climates

Climate	Neutral temperature °C		Comfort range °C		Author
	Winter	Summer	Winter	Summer	
Western/middle Europe	n/a	n/a	18–23[a]		Matzarakis and Mayer 1996
Subtropical (Taiwan)	23.7[b]	25.6[b]	26–30[c]		Lin 2009; Lin and Matzarakis 2008
Subtropical (Sydney)	28.8	22.9	n/a	n/a	Spagnolo and de Dear 2003
Hot arid, urban park (Cairo)	26.5[d]	27.4[d]	22–30	21–29	Mahmoud 2011
Hot dry (Damascus)	23.4	15.8	21–n/a	n/a–31	This study

[a] Theoretical comfort scale for all seasons

[b] Neutral temperatures in Taiwan were calculated by Lin (2009). The summer, spring and fall in Taiwan are defined as the hot season whereas the winter is called cool season (Lin 2009)

[c] One comfort range for the hot and cool seasons together (Lin and Matzarakis 2008)

[d] Neutral temperatures were calculated as the average values of the neutral temperatures in nine measurement locations in an urban park in Cairo

Table 9 Comparison of neutral temperatures and comfort ranges of the OUT_SET* index in different climates

Climate	Neutral temperature °C		Comfort range °C		Author
	Winter	Summer	Winter	Summer	
Subtropical (Taiwan)	28	29.3	n/a	n/a	Lin et al. 2011
Subtropical (Sydney)	33.3	23.3	n/a	n/a	Spagnolo and de Dear 2003
Hot dry (Damascus)	35.1	23.1	27.7–n/a	n/a–31	This study

in their study in Lisbon that clothing values varied between 0.24 and 1.75 mainly as a result of seasonal and daily variations in air temperature and wind conditions. Similarly, the studies of Nikolopoulou and Lykoudis (2006) in different countries in Europe, and that of Lin (2009) in Taiwan, found a strong relationship between average air temperatures and clothing. Lin (2009) also found a strong relationship between PET and clothing values, and concluded that changing clothing is one of the individual ways of thermal adaptation. As expected, this study found that the insulation value of people's clothing tend to decrease with increasing temperatures. The summer (hot season) values in this study are similar to those of Taiwan—around 0.6 clo (Table 7). The winter (cool season) values are, however, much higher in Damascus due to much colder winters. The study reveals that, in the case of Damascus, the choice of clothing is to some extent also linked to cultural aspects; in the winter, high clothing values (about 2 clo) occur also at the sensation "slightly cool" (−1) (Fig. 10). These clothing values are represented by values far above the regression curve. Thus in the winter, some people adjust their clothing according to the weather, whereas others use heavy clothing although it is only slightly cold. Hence, the dress code of some of the people of Damascus seems to depend on cultural traditions rather than climate, whereas most people choose their clothing according to the weather conditions when they feel thermally uncomfortable.

Thermal comfort limits for urban design in Damascus

The results of this study give valuable information regarding which comfort limits urban designers in Damascus should aim at. The primary aim could of course be to identify the thermal comfort zone. However, due to the lack of data for spring and autumn, in addition to the considerable difference between summer and winter, the lower and upper limits of the comfort zone for each of these seasons would be enough for architects and planners to apply. In addition, applying the lower and upper limits of the winter and summer comfort zones, respectively, in urban design will lead to more suitable proposals regarding microclimate because the comfort requirements for the most extreme weather conditions will be achieved, and these limits in turn will be valid for the entire year.

This study illustrates that the OUT_SET* index has better correlation with TSV and thermal unacceptability than the PET index, and this is due to the role of clothing and activity that OUT_SET* takes into account as input data. Thus, the use of OUT_SET* is more suitable than PET. But, on the one hand, the choice of thermal comfort index depends on the aim of the study. Among the tested indices, ET* does not take variations in wind speed into account and is thus less suitable for this reason. If the aim of the study is only to assess and evaluate the physical environment independently of people's sensations, e.g. if the aim is to compare the thermal comfort of different design proposals through simulations, the urban designer or researcher can use any of the other indices tested in this study. If, on the other hand, the aim is to assess the thermal environment taking into account people's thermal sensation, one can use an index such as OUT_SET* or PMV that takes clothing and activity into account. The use of these indices however requires knowledge—or at least an estimate—of people's clothing and activity. The fact that OUT_SET* is expressed in °C makes it easier to interpret than PMV. The PMV index is also restricted to moderate environments near neutrality (Spagnolo and de Dear 2003).

Conclusions

This study assessed the microclimate of the outdoor urban environment and investigated the relationship between different thermal comfort indices and people's actual thermal sensation in the hot dry city of Damascus. Thermal conditions of different outdoor environments vary considerably, mainly as a function of solar access. It was concluded that the urban design in Damascus needs to include well shaded spaces for pedestrians—e.g. by using high building density or vegetation—to protect pedestrians in summer as well as open spaces to provide solar access in winter.

Furthermore, this study defined the upper summer and lower winter comfort limits for PET and OUT_SET* in hot dry Damascus. This is important information for urban designers aiming for climate-conscious urban design. The study also showed the influence of culture and traditions on clothing. While most people choose the clothing according to the climate, some people in Damascus are influenced by their cultural traditions when they choose clothes to wear.

This study highlighted the importance of a climate-conscious urban design and design flexibility. It is important

to consider microclimate and thermal comfort in the urban design process and requirements for a climate-conscious urban design should preferably be included in the planning regulations for cities such as Damascus. In addition, existing urban environments in Damascus could be modified in order to provide a better outdoor thermal environment. Such studies could enhance the thermal comfort and suggest improvements to existing urban planning regulations.

Further studies are needed since this and other studies have shown that actual thermal sensation is affected not only by microclimatic parameters (air temperature, solar radiation, relative humidity, and wind speed) and personal parameters (people's activity and clothing). Future studies should look into other parameters such as the aesthetic qualities of the place, as well as psychological factors such as thermal history, emotional state, and attitude towards urban outdoor exposure. Furthermore, measurements and thermals sensation questionnaires that cover all seasons are needed in order to define the annual comfort zone for Damascus.

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