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Thermal Comfort in Outdoor Urban Spaces: analysis across different European countries

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Abstract

This paper presents some of the findings of the European project, RUROS, primarily concerned with the environmental and comfort conditions of open spaces in cities. The results of the microclimatic and human monitoring, in relation to the thermal environment and comfort conditions in open spaces are presented. The database consists of nearly 10,000 from field surveys in 14 different case study sites, across 5 different countries in Europe. The findings confirm a strong relationship between microclimatic and comfort conditions, with air temperature and solar radiation being important determinants of comfort, although one parameter alone is not sufficient for the assessment of thermal comfort conditions. Overall comfort levels are over 75% for all cities on a yearly basis. There is also strong evidence for adaptation taking place, both physically, with the seasonal variation in clothing and changes to the metabolic rate, as well as psychologically. Recent experience and expectations play a major role and are responsible for a variation over 10 °C of neutral temperatures, largely following the profile of the respective climatic temperatures on a seasonal basis, across Europe. In this context, perceived choice over a source of discomfort is another important parameter for people in open spaces.

Keywords: outdoor thermal comfort, microclimate, adaptation, urban design

1. Introduction

There is strong public interest in the quality of open urban spaces and it is acknowledged that they can contribute to the quality of life within cities, or contrarily enhance isolation and social exclusion. In this context, microclimatic conditions have begun being viewed as integral to the success of an open space, indirectly a critical parameter for the use of outdoor spaces in the urban environment. Responses to the microclimate may be unconscious, but they often result in a different use of open space in different climatic conditions.

However, there is a significant lack of information on data for evaluation of comfort conditions in outdoor spaces, which in effect will assist the design and planning of such spaces. Furthermore, it will assist in the development of large-scale projects such as EXPO parks, which rely strongly on the use of the area by pedestrians.

Theoretical thermoregulatory models developed for the indoor environment are not viewed as adequate for describing the thermal comfort conditions outdoors, due to the great complexity of the outdoor environment, and variability temporally and spatially.

The need for empirical data from filed surveys on the subjective human parameter in the outdoor context has been acknowledged, as this would provide a broader perspective from which to view comfort in urban spaces. This realization, in turn, has given rise to increased research on the topic in the last years [1-6]. Field surveys have indeed been viewed as necessary across different disciplines, varying from the field of architecture, to geography and urban climatology, on a world wide scale.

2. Project RUROS

Previous research undertaken by the author, in Cambridge UK has shed some light on the effect of microclimatic conditions on the use of outdoor spaces in the urban environment [1], where

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responses to the microclimate often resulted in a different use of open space at different climatic conditions. Thus, understanding the richness of urban outdoor microclimatic characteristics and the comfort implications for the people using them, opens up new possibilities for the development of urban spaces.

Based on this evidence, a wide-scale project was organised, with the aim of examining and evaluating a broad range of comfort conditions –thermal, visual, audible– across Europe. Project RUROS (Rediscovering the Urban Realm and Open Spaces) aimed to improve the urban realm and revitalise city centres, by integrating social and environmental objectives. This has been possible with extensive field surveys to understand and evaluate comfort conditions across Europe, encompassing the climatic variation, urban morphology, cultural background and plethora of personal differences, characterizing the users of open spaces. In this respect, RUROS has provided a unique integrated study of the urban environment, both for the issues it has investigated as well as the surveys carried out across Europe.

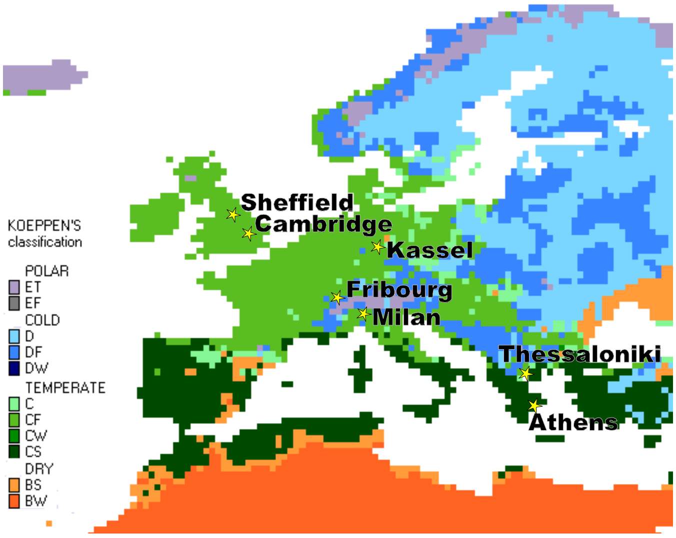

Figure 1: The different cities participating in project RUROS and the climatic zones of Europe according to Koeppen's classification [7]

Two case studies of different nature were examined in each of the cities participating in the project (Fig. 1), Athens (GR), Thessaloniki (GR), Milan (I), Fribourg (CH), Kassel (D), Cambridge (UK) and Sheffield (UK), used as the medium for examining comfort conditions outdoors. The sites were selected to represent a wide variation of typologies, functions, types and activities representative in the different cities.

2.1 Field surveys

Detailed microclimatic monitoring was carried out with the use of a portable mini-weather station, while people were studied in their natural environment through structured interviews and observations, to evaluate the comfort conditions people experience and their perception of the environment. Individuals' characteristics and behavioural patterns were also taken into account. The structured interviews, with standard questionnaires, aimed to represent the views of a broad range of users. Environmental monitoring was taking place while the interviews were carried out, in order to record the microclimatic parameters the interviewees were experiencing.

The field surveys began in July 2001 and were completed in September 2002, for all cities, covering the different seasons; summer, autumn, winter and spring. Each site was monitored for a full week each season, to obtain the weekly pattern of use.

The time period that the surveys were carried out varied according to the season, also aiming to obtain the daily, as well as the seasonal, pattern of use. The periods were roughly separated in four different categories, morning period (10:00 - 11:59), midday period (12:00 - 14:59), afternoon (15:00 - 17:59) and evening period (18:00 - 20:59). Their duration also varied according to the season, i.e. in the summer surveys were running until 21:00, whereas in autumn, the surveys were running until 17:00, for security reasons as it was getting dark earlier.

2.1.1 Environmental monitoring

The field surveys took place periodically within a year, to get the seasonal variation, which affects the use of space. The objective environmental parameters investigated are related to the thermal, visual as well as acoustic environment. The nature of the work required close monitoring of the environment people were exposed to, thus the equipment had to be portable and easily transported around.

The environmental parameters monitored are air temperature, solar radiation, wind speed and humidity. These were measured through a psychrometer with forced ventilation measuring dry and wet bulb air temperature, a Pt-100 globe thermometer and an omni-directional hot-wire anemometer. The sensors were carefully selected to conform to ISO 7726 [8].

A grey globe thermometer was considered more appropriate for comfort studies outdoors, as opposed to the customary black coloured globe thermometer. A black thermometer without correction for people's solar thermal reflectivity assumes that all people in the sun are black wearing black clothing, therefore overestimating MRT in these conditions. To ensure consistency among the different teams that would be carrying out the field surveys, a globe of matt grey colour of 0.5 reflectance was employed.

For the acoustic and luminous environment, sound pressure levels and illuminance levels were recorded.

2.1.2 Human monitoring - Questionnaire

People were studied in their natural environment, to evaluate their perception of the thermal, luminous and acoustic environment. Issues affecting the use of space (patterns of use, groups of people using the space, preferences within the area, etc.) were also investigated in a questionnaire compiled for the study. This paper concentrates on evaluation of the thermal environment and comfort conditions.

The interviewees were reporting their evaluation of different microclimatic parameters either on a 5- or 3-point scale, as well as their assessment of their overall comfort state (Table 1).

Table 1: Extract from the questionnaire related to the thermal environment

At the moment, do you find it:
very cold
cool
neither cool nor warm
warm
very hot
What do you think of the **sun** at this moment? *(only asked if sunny)*
you'd prefer more
OK
too much sun
What do you think of the **wind** at this moment?
stale
little wind
OK
windy
too much wind
What do you think of the **humidity** at this moment?
damp
OK
dry
Are you feeling **comfortable**?
yes
no

3. Data Analysis

Extensive statistical treatment of the data was carried out and a Statistical Analysis Scheme was developed to handle the bulk of the data and ensure the validity of the results. Overall, nearly 10,000 interviews were carried out at the five different cities across Europe, which forms a significant database with a wealth of information. More specifically, the number of people interviewed at the different cities and seasons is presented in Table 2.

Table 2: Number of interviews carried out at the different cities, at different seasons, in the context of RUROS

	Summer	Autumn	Winter	Spring	Year
Athens	418	360	418	307	1503
Thessaloniki	600	509	335	369	1813
Milan	308	393	207	265	1173
Fribourg	452	427	540	501	1920
Cambridge	341	185	85	337	948
Sheffield	301	216	200	291	1008
Kassel	301	209	74	240	824
total per season	2721	2299	1859	2310	9189

3.1 Microclimatic data

A summary of the average climatic information for the different interview periods, at the different cities across Europe are presented in Table 3. Air temperature (°C), relative humidity (%), wind speed ($m.s^{-1}$) and globe temperature (°C) as an indication of solar radiation, are presented for the different monitoring sites, the closest meteorological station and the long term climatic average for the respective seasons.

Overall, the microclimatic data recorded at the interview periods are in accordance to the data recorded at the meteorological station for all cities and seasons, with small differences attributed to the effect of the urban fabric. Similarly, the large differences in wind speeds are due to the fact that at the different sites wind speed was measured at about 1m high, whereas at the meteorological station the respective height is 10m, unobstructed by buildings and vegetation.

However, comparing the recorded data with the average climatic data there are significant differences, as far as the air temperature is concerned. Based on climatic analysis performed by the Climatic Research Unit of the University of East Anglia [9], this could be explained by the fact that the years 2001 and 2002, when our surveys were carried out, have been within the 10 hottest years for Europe since 1856. This is the case for all cities and particularly apparent for spring and winter, where, e.g. in Firbourg the winter departure is 7 °C, while in Milan and Cambridge, in spring, the difference between the meteorological data and average climatic data for the period is nearly 11°C and 14 °C respectively. Autumn values are in same cases cooler than the climatic ones, yet this is due the late dates when the surveys were carried out.

Table 3: Average climatic information during the interview periods for the different cities at the different seasons, as recorded (i) on site, (ii) the official meteorological station and (iii) the climatic average.

		Summer			Autumn			Winter			Spring		
		On Site	Meteo Station	Climatic	On Site	Meteo Station	Climatic	On Site	Meteo Station	Climatic	On Site	Meteo Station	Climatic
Athens	Tair (°C)	30.1	31.5	27.0	18.8	19.0	19.7	16.4	15.6	11.0	21.9	22.0	16.3
	RH (%)	47	41	49	62	65	61	52	55	69	49	48	63
	Ws ($m.s^{-1}$)	1.0	4.1	7.3	0.7	2.4	6.9	0.7	2.9	7.6	1.1	5.1	6.6
	Tglobe (°C)	31.2			21.6			20.4			25.4		
Thessaloniki	Tair (°C)	26.5	27.5	25.7	9.9	10.6	16.3	15.2	15.2	6.3	21.3	20.7	14.5
	RH (%)	41	48	55	51	57	70	59	69	76	63	64	68
	Ws (m/s)	0.2	2.2	6.1	0.2	1.9	5.1	0.2	1.4	5.7	0.2	1.8	5.3
	Tglobe (°C)	28.1			11.2			19.6			25.7		
Fribourg	Tair (°C)	23.2	23.1	16.8	11.7	11.8	8.8	6.8	6.5	-0.2	14.0	12.8	8.6
	RH (%)	43	55	67	56	66	78	62	64	80	50	61	68
	Ws ($m.s^{-1}$)	1.1	2.3	2.7	1.0	2.0	2.5	1.2	2.7	2.9	1.1	2.6	3.1
	Tglobe (°C)	28.1			14.9			9.5			18.0		
Milan	Tair (°C)	26.4	26.0	22.0	14.4	15.5	13.0	10.8	9.2	2.6	23.5	23.2	12.4
	RH (%)	61	61	71	63	60	80	58	60	83	56	57	73
	Ws ($m.s^{-1}$)	0.5	1.9		0.5	1.9		0.9	3.2		0.6	1.9	
	Tglobe (°C)	28.6			16.8			13.2			26.4		

Cambridge	Tair (°C)	23.1	22.7	16.3	8.9	8.1	10.7	10.9	9.4	4.5	22.9	24.7	8.8
	RH (%)	56	55	77	74	77	86	59	63	90	56	59	78
	Ws (m.s^{-1})	1.0	3.0		0.5	3.0		0.9	5.4		1.0	4.0	
	Tglobe (°C)	25.3			9.3			12.2			25.5		
Sheffield	Tair (°C)	21.3	20.4	15.7	16.7	16.0	10.2	9.5	8.2	4.4	13.2	11.8	8.6
	RH (%)	60	77	69	69	85	81	63	87	85	49	76	70
	Ws (m.s^{-1})	1.0	3.9		0.9	4.8		0.5	5.0		0.5	2.6	
	Tglobe (°C)	23.5			18.1			11.7			16.2		
Kassel	Tair (°C)	21.9	21.6	16.6	16.5	16.0	9.0	5.4	4.7	0.6	22.2	21.2	8.1
	RH (%)	67	70	73	76	79	81	60	59	84	58	59	71
	Ws (m.s^{-1})	1.2	3.3		1.1	2.7		1.2	2.2		1.2	2.8	
	Tglobe (°C)	23.3			17.9			6.8			24.4		

3.2 Correlations between microclimate and comfort

ASHRAE defines comfort as a “condition of mind in which satisfaction is expressed with the environment” [10], a definition more diverse than one might at first anticipate. The complexity of the definition and understanding of comfort by people participating in the surveys will also become apparent in the analysis of the following Sections, while trying to disentangle the effect of thermal sensation and that of other variables.

People’s thermal sensation was reported on a 5-point scale, varying from “very cold” (-2) to “very hot” (+2) (Table 1), which has been defined as the Actual Sensation Vote (ASV). Investigation of the correlations between the microclimatic variables and ASV, across the whole database, revealed that ASV correlates better with globe temperature ($r = 0.53$, $p<0.01$, Pearson correlation coefficient), than with air temperature ($r = 0.43$, $p<0.01$), which is attributed to the radiant effect of the sun. The relatively weak correlations between microclimatic variables and ASV indicate that one parameter alone is not sufficient for the assessment of thermal comfort conditions.

The correlation coefficient between sun vote with air temperature and globe temperature is 0.31 and 0.35 respectively ($p<0.01$). The thermal effect of the sun vote also appears when compared with ASV ($r = 0.23$, $p<0.01$). The relationship between wind speed and wind vote is moderately weak ($r = 0.26$, $p<0.01$), implying increasing comfort moving from stale to moderate wind conditions and discomfort as wind increases further affected, though, by the desired cooling effect of wind at different seasons.

Looking at the actual figures of overall comfort, these are very high for all cities and seasons (Fig. 2), demonstrating that in the vast majority people are satisfied with the environment. In fact, the percentage of overall comfort on a yearly basis is over 75% for all cities, reaching 91% for Cambridge. Even in Athens in the summer, when high air temperature is frequently a source of discomfort, overall comfort is 73%, reaching 93% in winter. The lowest figure is found in Kassel, in winter, where only 32 of the 74 people (43%) have reported being comfortable.

In order to identify sources of discomfort, as evaluated from the different survey responses, analysis is carried out on the effect of wind, humidity and thermal sensation on the overall feeling of discomfort, on a seasonal basis.

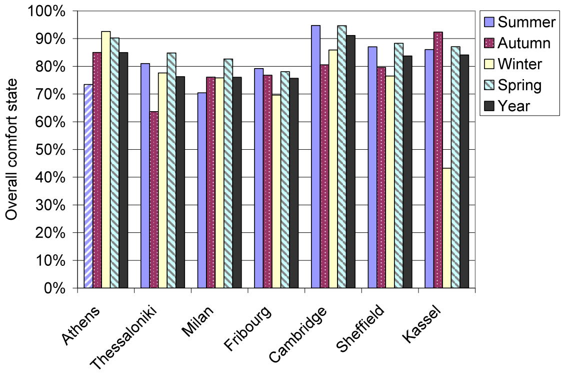

Figure 2: Percentage distribution of overall comfort state, for the different cities, at different seasons.

Figure 3 concentrates on the wind environment, presenting seasonal analysis of the percentage of overall discomfort as voted for the different evaluation categories of the wind environment, for the different cities.

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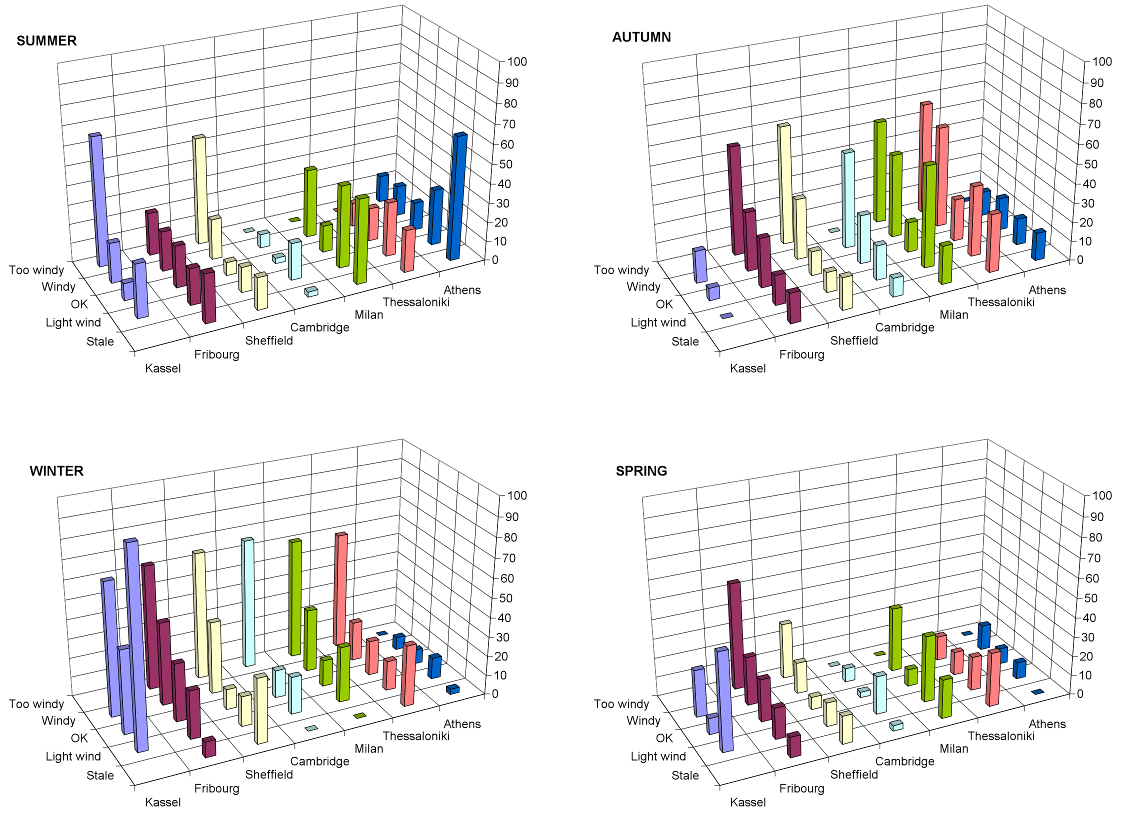


Figure 3: Percentage distribution of responses to overall discomfort and evaluation of the wind environment, for the different cities, at different seasons.

In the summer, strong winds (category, “too windy”) are associated with discomfort in northern climates, such as Kassel and Sheffield (wit the lowest mean Tair of 21.3 °C and 21.9 °C respectively), whereas they appear more tolerant in places with higher air temperatures. In the latter areas, stale conditions are a contributing factor to discomfort, particularly in Athens, where average air temperature for the season exceeds 30 °C. In autumn and winter strong winds are a source of discomfort for all cities.

Moving on to humidity, Figure 4 presents the seasonal analysis of the percentage of overall discomfort votes for the different humidity evaluation categories, for the different cities.

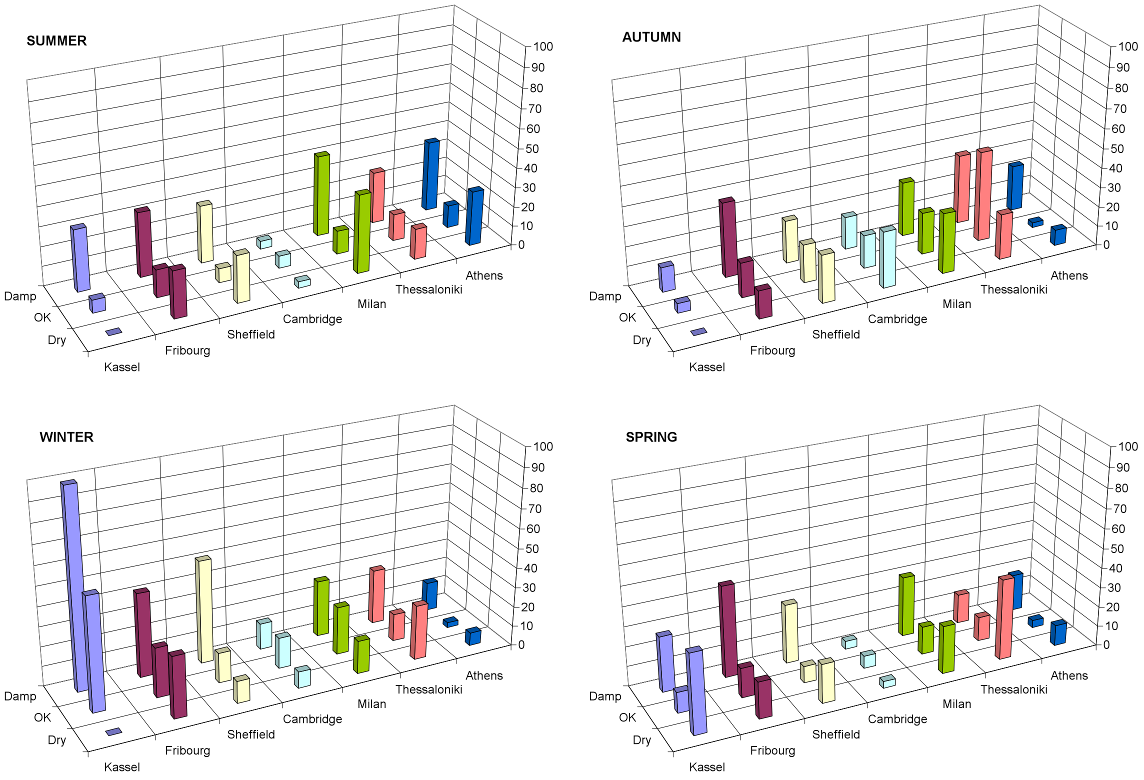


Figure 4: Percentage distribution of responses to overall discomfort and evaluation of the humidity levels, for the different cities, at different seasons.

Humidity appears to have good correlation with comfort, as irrespective of season, “damp” or “dry” conditions are associated with an increase in discomfort. However, it should also be borne in mind that in general, people are not very good at judging changes in humidity levels, unless relative humidity is very high or very low and normally in conjunction with temperature conditions enhancing the effect of humidity. Thus it is the extremes that people notice and their evaluation departs from the “OK” vote.

Examining people’s Actual Sensation Vote (ASV) with overall discomfort (Fig. 5), shows that in the majority of cases, the extreme “very hot” (+2) and “very cold” (-2) votes are associated with increased levels of discomfort. As expected, the higher frequency of +2 and -2 votes are in the summer and winter respectively. It is also interesting to notice that in cities with high air temperature and humidity levels, such as Thessaloniki and Milan, even “warm” (+1) votes have increased discomfort levels indicating a significant second-role for relative humidity in the overall comfort sensation.

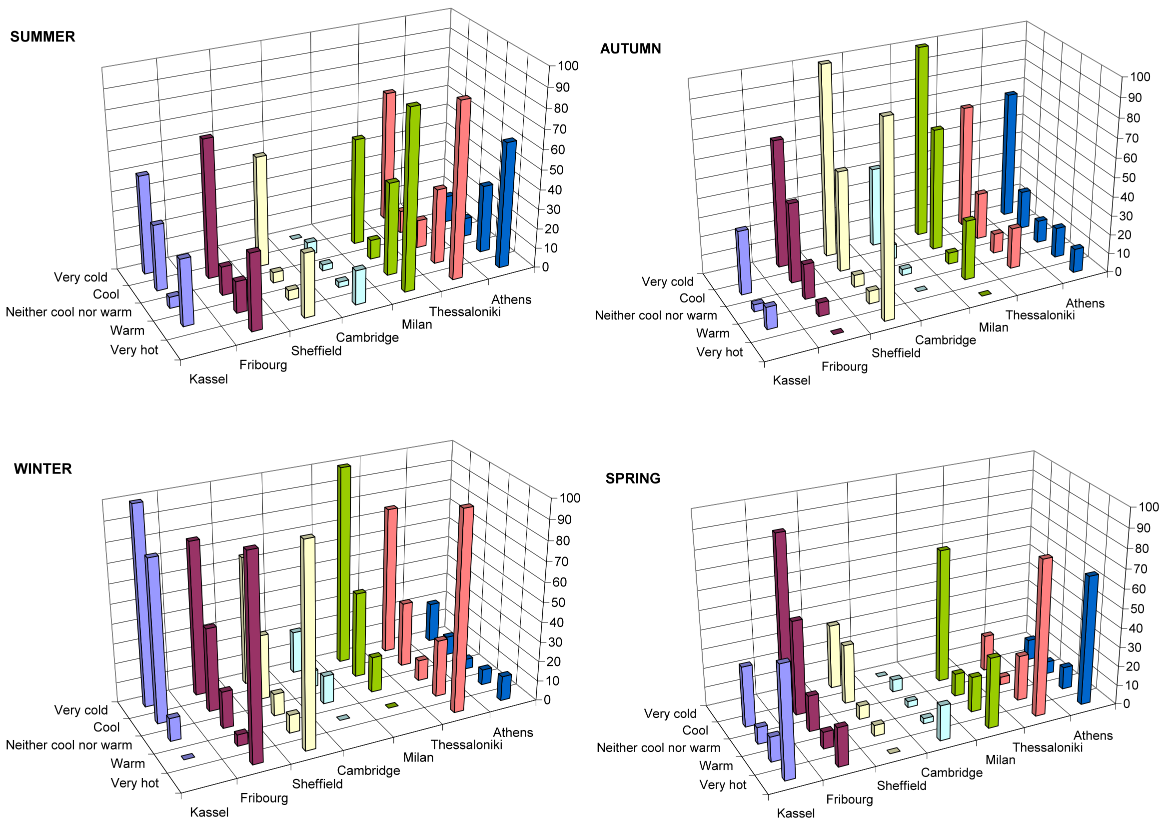


Figure 5: Percentage distribution of responses to overall discomfort and evaluation of the thermal sensation, for the different cities, at different seasons.

So far we have concentrated on identifying microclimatic parameters as sources of discomfort. Beyond the overall discomfort, it is worth examining the evaluation of thermal sensation in the outdoor environment, as distributed for the different votes, irrespective of the actual comfort state.

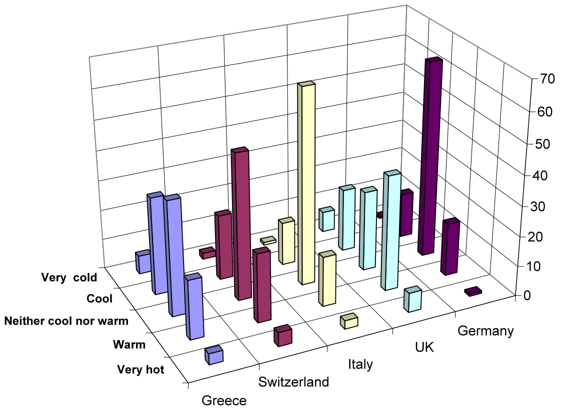


Figure 6: Percentage distribution of the Actual Sensation Vote of the interviewees (ASV) throughout the year, for the different countries

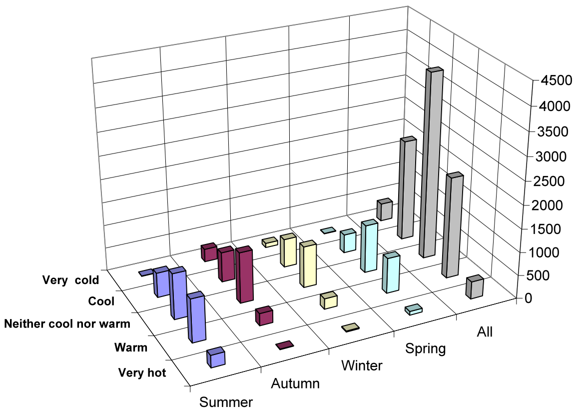


Figure 7: Distribution of the Actual Sensation Vote of the interviewees (ASV), for the different seasons

In terms of the number of people that have voted in the region of $-1 \leq ASV \leq +1$, it is interesting to notice that it lies around 90% of the population that has participated in the surveys for each country, despite the great variation of the microclimatic conditions (Fig. 6). Only 4% of these people have reported to be feeling “very hot” (+2) and another 4% has opted for “very cold” (-2), figures regarded as acceptable even in the tightly controlled indoor environment. The majority of the votes is for neutrality (0), with 44%, with “warm” (+1) and “cool” (-1) votes at a nearly equal split of 24%.

In Italy and Germany, “neither warm nor cool” votes account for 65% (of the total 1173 interviews in Italy and 824 interviews in Germany), although only 9% corresponds to winter in Germany) (Fig. 6). Even more interesting, in the UK (1956 interviews), 39% of the population has reported feeling “warm”, with neutrality votes (0) following with 27%.

Overall, a shift towards cooler votes is noticeable, as one moves from summer to spring / autumn and finally winter (Fig. 7). Adaptation mechanisms are to be attributed for the very small amount of extreme votes under a very wide range of climatic conditions, as explained in Section 3.4.

Looking back into the number of people who have reported as feeling comfortable (Fig. 2), it is interesting to identify the importance of thermal sensation and thermal comfort in the overall comfort state. Employing a binary code with the category of discomfort denoted as 0 and comfort as 1, it is possible to follow similar categorisation for the rest of the parameters, thermal sensation, evaluation of wind and evaluation of the humidity. Discomfort is allocated at the extreme categories: ±1in the case of 3-point scales and ±2 with 5-point scales. Thus, it is possible to tabulate the role of each aspect of the environment in the overall comfort state.

Table 4 concentrates on the percentage of people feeling comfortable in the different cities and their feeling of comfort or discomfort, in relation to thermal sensation (1st digit), wind (2nd digit) and humidity (3rd digit), and the possible combinations of these categories, all presented with the use of binary codes, “0” representing discomfort and “1” comfort. Hence, a “101” category demonstrates comfort in relation to thermal sensation, discomfort in terms of wind and comfort for humidity.

As emphasis is on thermal sensation, all combinations of thermal discomfort are presented on the left part of the Table and all combinations of thermal comfort on the right. It is interesting to notice that comfort with respect to thermal sensation, is the most dominant parameter in determining overall comfort. Satisfaction with humidity levels normally increases the percentage of satisfaction (category “101”), e.g. for Athens reaches 97% and for Kassel 100%. The role of humidity can also be examined in the case of thermal discomfort (columns “000” and “010”), where e.g. for Athens, Sheffield and Thessaloniki comfort levels almost double with satisfaction with humidity, even though in thermal discomfort. Wind does not appear to have as big an influence on increasing overall thermal comfort levels, e.g. from column “100” to “110” the percentage increase is relatively small. This is presumably due to the fact that its effect is strongly dependent on air temperature, while higher wind speeds than found in most of the surveys are required to make a noticeable effect.

Table 4: Percentage of people in overall comfort state, and their evaluation of comfort or discomfort presented with a binary code (“0” for discomfort – “1” for comfort) in relation to thermal (1st digit), wind (2nd digit) and humidity (3rd digit) sensation

Feeling Comfortable Overall (%)								
	000	001	010	011	100	110	101	111
Athens	26	57	45	95	79	82	97	96
Cambridge	76	80	77	67	100	96	96	95
Fribourg	50	33	49	56	67	70	82	84
Kassel		0	0	40	0	77	100	88
Milan	11	0	21	33	57	73	69	84
Sheffield	18	33	55	69	58	79	78	91
Thessaloniki	18	29	41	28	72	81	86	86

3.3 Neutral temperatures

Another interesting way of examining thermal sensation is through the use of neutral temperatures, i.e. the thermal conditions where people feel neither warm, nor cool, but neutral. This term was first introduced by Humphreys (1975), when he showed that variation of the neutral temperature is associated with the variation of the mean temperature [11].

Probit analysis is used to identify changing points of a binary response-variable in relation to a stimulus-variable. Considering ASV to be the basis of a binary response variable we are interested in obtaining temperatures at which a certain percentage, say 50%, of the interviewees would be in the verge of changing their ASV to the next higher value.

Ballantyne (1977) suggested probit analysis to calculate neutral, or preferred as he called them, temperatures [12]. This, for any certain level of percentage of interviewees, would be the centre value of the distance between the curve describing the probability of someone changing his vote from cooler than neutral to neutral or warmer (transition curve), thus entering the neutrality zone, and the transition curve describing the probability of someone changing his vote from neutral or cooler to warmer than neutral thus exiting the neutrality zone.

Thus, a set of binary response variables was created from ASV, describing the partition of the interviewees on each side of every ASV level. Initially simple probit analysis was used, using air temperature as stimulus, however, for several cases the resulting transition curves were crossing each other, not allowing for meaningful results to be drawn. The existence of some "extreme" cases resulting in significant increase of the total variance probably was responsible for that, so forced parallel probit analysis, a variation that forces all transition curves to be parallel, had to be applied.

Neutrality zones were determined for each city on a seasonal, as well as on a yearly basis, according to the methodology described above. Table 5 presents the centre values for these neutrality zones at the level of 50% probability of transition henceforth called neutral temperatures.

Table 5: Neutral temperature (°C) (centre value of the probit neutrality zone at the 50% probability of transition level, for the different cities at different seasons.

	Year	**Summer**	**Autumn**	**Winter**	**Spring**
	50	50	50	50	50
Athens	22.8	28.5	19.4	*21.5**	24.3
Thessaloniki	25.3	28.9	24.7	15.0	18.4
Fribourg	12.9	15.8	13.2	11.9	13.2
Milan	18.3	21.5	24.6	*21.1*	20.7
Cambridge	17.8	18.0	23.2		17.6
Sheffield	13.3	15.8	16.7	10.8	11.8
Kassel	18.5	22.1	15.8	*15.2*	17.2

*numbers in italics are not statistically significant at a 95% confidence level.

The majority of the interviews were carried out in the summer, whereas in winter, the number of interviews was limited in comparison, while in some cases the variation was extremely high, so it would be advised not to put great emphasis on the winter neutral temperatures of Athens, Milan and Kassel, while Cambridge is not even presented. However, when combining all the dataset together, it is interesting to note the great variation of neutral temperature across Europe, which is over 10 °C (Table 5). The annual neutral temperature, i.e. the temperature where people feel neither warm nor cool is just below, 23 °C for Athens and 13 °C for Fribourg.

Presenting neutrality zones graphically, with the relevant transition curves, it is interesting to examine, the seasonal analysis for cities where there are no problems of statistical significance, e.g. Thessaloniki and Fribourg. Figure 8 presents the transition curves delineating the neutrality zone for each season at Thessaloniki and Fribourg. The width of a neutrality zone could be conceived as an indication of the extent of tolerance of the interviewees possibly reflecting differences existing between the various cities/climatic regions of Europe. The neutrality zone of Thessaloniki appears to be significantly wider for the intermediate seasons of spring and autumn, than in the summer and winter, while the relevant shift of the mean values is also important.

More specifically, the comfort zone for spring and autumn is as wide as 17.6 °C and 13.5 °C respectively, whereas for summer and winter, it is only 5.9 °C and 9.6 °C wide. Furthermore, the shift of the centre values means that the autumn comfort zone is found at higher neutral temperatures than spring, 24.7 °C as opposed to 18.4 °C. For winter and summer these values reach more extreme values at 15.0 °C and 28.9 °C respectively. On the other hand, the data from Fribourg indicate a smaller seasonal variation of the neutrality zone width, especially when transitional seasons are grouped together, while the centre values also present a moderate to low seasonal variation. This difference in the neutrality zone location and spread could be due to difference in behaviour between the southern and the northern cities, a result of experience to a different range of climatic conditions (see Section 3.4) and difference in sensitivity to heat and cold described at the end of this Section.

Furthermore, both autumn and spring appear to follow the behaviour of the preceding season. In this context, warmer temperatures are expected in autumn, following the hot climatic conditions of the summer, whereas in spring, cooler temperatures are regarded as comfortable, following the cold conditions of winter (also apparent In Table 5). This appears to be due to the effect of adaptation and the role of recent experience and expectations, as also explained in the following Section.

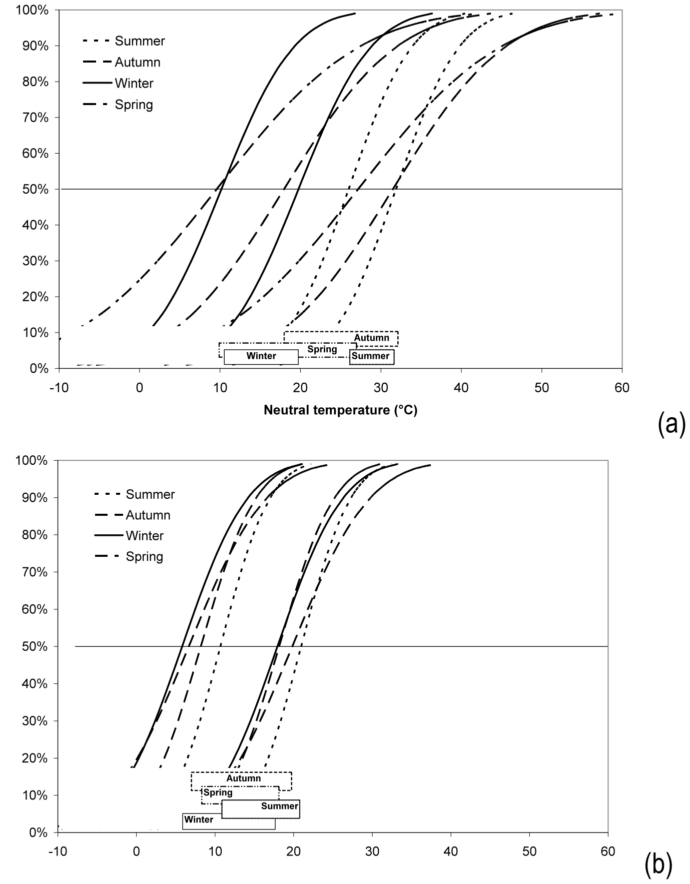
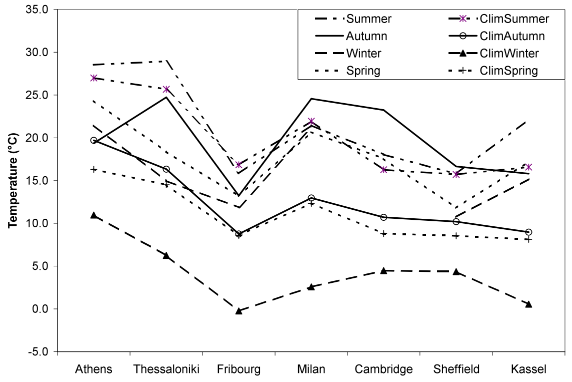


Figure 8: Percentage distribution of change of neutral temperature (°C) to shift from cool to neutral and from neutral to warm for (a) Thessaloniki and (b) Fribourg at different seasons. Width of comfort zone for the different seasons is transposed at the bottom of the chart.

Another issue arises from comparing the neutral temperatures with the respective long term climatic temperatures for the different cities (Fig. 9). Neutral temperatures, as have been calculated through probit analysis, appear to follow the profile of the respective climatic temperatures on a seasonal basis, which seems to be the case for all cities. Furthermore, the difference between the two sets of data, i.e. neutral and climatic temperature is particularly interesting. In the summer the two sets of temperature lie very close, while the biggest difference is noticed in winter. The intermediate seasons lie in between, with spring neutral temperature being closer to the respective climatic air temperature than autumn is, for most cities.

Examining the difference between the two sets of data further, i.e. neutral temperature and climatic air temperature, appears to be inversely proportional to the mean climatic air temperature of the region. Thus, the bigger the climatic air temperature is, the closer neutral temperature is to it, as is the case of summer. This appears to have a physical explanation as well, since in warm conditions – provided the heat is not life-threatening or exceeds the skin temperature– people have the required mechanisms to adapt more easily than in cold conditions. This rapid adaptation of the human body to heat has also been proven by Höppe, with the use of theoretical (thermophysiological) modelling [13].

Sensitivity is thus greatest at cold rather than hot conditions. This sensitivity to cold has also been found in an earlier study of Nikolopoulou *et al.* [1, 14] in field surveys in Cambridge, while investigating the influence of thermal sensation on people's duration of exposure to the specific conditions. They found that in the range of sensation votes of -1 to +1 duration was longest, decreasing outside that zone, particularly noticeable at sensation votes of -2. It seems that this sensitivity to cold provides an early warning for the subject to react and prevent further cooling of the organism, which would be hazardous.



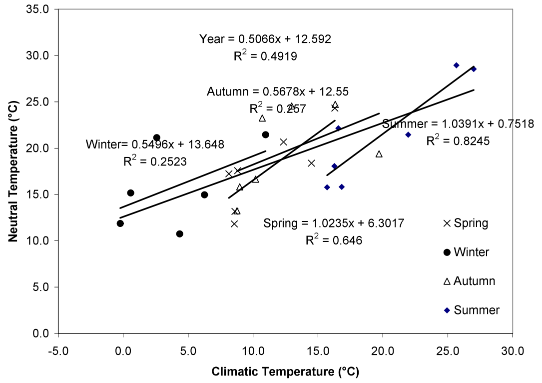


Figure 9: Neutral temperatures compared with the relevant climatic air temperature for different seasons, for the different cities.

Figure 10: Seasonal variation of neutral temperature (°C) as a function of climatic air temperature (°C). The respective values for each city are depicted by single point, thus there are seven points for each season.

Finally, returning to the seasonal analysis to examine the mean neutral temperature as a function of the mean climatic air temperature demonstrates that summer behaves very similarly to spring, as does winter to autumn. Although different magnitudes are foreseen for the different seasons, as already discussed in Figure 8 and also apparent in Figure 10, nevertheless the slope of the regression lines for the two groups of seasons (summer – spring, winter – autumn) is similar. More specifically, in the cooler seasons, neutral temperature appears to be less sensitive to changes in the climatic air temperature, with neutral temperature found at significantly higher values than the corresponding air temperature. Aggregating the data on a single group for a yearly pattern, it appears to follow the slope of the cooler seasons, emphasizing the sensitivity of the human body to the cold, with corresponding implications for thermal comfort conditions.

3.4 Evidence for adaptation

The term 'adaptation' can be broadly defined as the gradual decrease of the organism's response to repeated exposure to a stimulus, involving all the actions that make them better suited to survive in such an environment. In the context of thermal comfort this may involve all the processes which people go through to improve the fit between the environment and their requirements and three different categories can be identified: physical, physiological and psychological.

Nikolopoulou *et al.* [15] defined physical adaptation in terms of the changes a person makes, in order to adjust oneself to the environment, or alter the environment to his needs. In this context two different kinds of adaptation were identified, *reactive* and *interactive*. In the former the only changes occurring are personal, such as altering one's clothing levels, position, etc., whereas in the latter, people interact, making changes to the environment in order to improve their comfort conditions, opening a window, opening a parasol, etc.

Physiological adaptation or physiological acclimatization implies changes in the physiological responses resulting from repeated exposure to a stimulus, leading to a gradual decreased strain from such exposure [16], thus not of central importance in this context.

Different people perceive the environment in a different way, and it is argued that human response to a physical stimulus is not simply a function of its magnitude, but also depends on the 'information' that people have for a particular situation. Psychological factors are therefore influencing the thermal perception of a space and the changes occurring in it. These have been analysed elsewhere [2] and are only briefly mentioned below:

- Naturalness of a space [17], as people appear to tolerate wide changes of the physical environment, provided they are produced naturally [2].
- Expectations, i.e. what the environment should be like, rather than what it actually is, greatly influence people's perceptions [2, 18, 19].
- Experience, directly affects people's expectations [20, 2].
- Time of exposure, as exposure to discomfort is not viewed negatively if the individual anticipates that it is short-lived [21-23, 2].
- Perceived control [22, 24], as people with a high degree of control over a source of discomfort, tolerate wide variations, are less annoyed by it, and the negative emotional responses are greatly reduced [2].
- Environmental stimulation [2], probably the main reason for the majority of outdoor activities. Comfortable conditions have been regarded as those where occupants feel neither warm nor cool, and it is increasingly believed that a variable, rather than fixed, environment is preferred whereas a static environment becomes intolerable [25, 26].

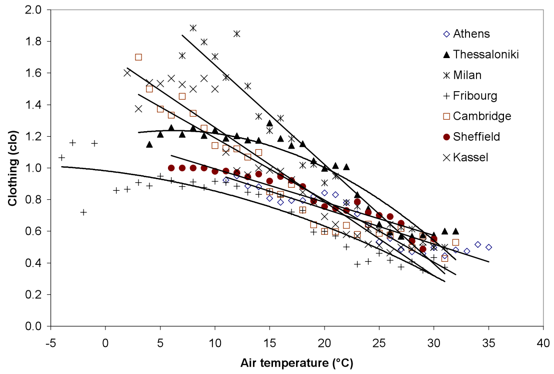
3.4.1 Physical adaptation

Due to the nature of the majority of open spaces, *interactive* physical adaptation is very limited and requires the presence of specific elements, such as movable shading devices, or panels for wind protection. In the few case study sites, where such an element existed, e.g. parasols at a cafeteria in Athens, these were operated by the manager of the place. Thus, particularly in public spaces, there is not an opportunity for users to interact with the environment.

On the other hand, *reactive* physical adaptation, i.e. personal changes was very frequent and exercised equally across Europe. The most common form is the seasonal variation of clothing. In fact the correlation between air temperature and clothing insulation levels is -0.61 ($p< 0.01$), denoting that as air temperature rises clothing insulation reduces, with people wearing lighter garments.

Plotting mean clothing levels (as defined by ISO 7730 [27]) as a function of mean air temperature, demonstrates this strong relationship, irrespective of geographic location (Fig. 11). All stations have an inverse linear relationship, with the exception of Thessaloniki and Fribourg, where the relationship is of second degree.

The data for Milan, Kassel and Cambridge has a higher slope, denoting a greater sensitivity of clothing to air temperature. Sunlight could also be an important factor for the cities with smaller sensitivity to air temperature, as Greece and Switzerland have higher frequencies of clear sky conditions. It is also interesting to notice that in Fribourg, clothing levels in winter are lower than other cities, rarely over 1 clo. This could be attributed to two reasons. Firstly, as described in Table 3, the surveys took place during years that were significantly warmer than the climatic average. Thus, in Fribourg the average air temperature recorded during the surveys in winter was 6.8 °C, whereas the mean climatic figure for this time of the year is -0.2 °C, which is significantly lower. Secondly, as Fribourg is near the Alps, the majority of the city's residents are frequently going to the mountains skiing where it is also significantly colder, exposing themselves to harsh thermal conditions. Thus it could be argued, that people there did not view the air temperature during the surveys as very cold, and the very thick garments were kept for when the air temperature would be lower.



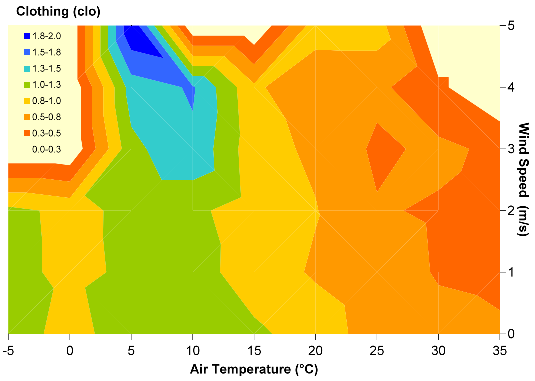


Figure 11: Variation of mean clothing levels (clo) as a function of mean air temperature (°C) for the different cities.

Figure 12: Variation of mean clothing levels (clo) as a function of mean air temperature (°C) and wind speed (m.s^{-1}) for all the cities together.

In order to investigate the relative importance of air temperature and wind speed in clothing insulation, all stations are combined together and are presented in a single map (Fig. 12). As there were very few cases with air temperature below 0 °C, primarily in Fribourg, it’s best to ignore that part of the chart. Figure 12 demonstrates that air temperature is the main determinant of clothing insulation. Wind speed becomes significant only at low air temperatures and particularly at high wind speeds, where it is the main contributing factor. It is at these conditions that the cooling effect of the wind is particularly undesirable, which is why the wind-chill index was initially developed at arctic conditions [28] and is normally used at cold climates.

Changes to the metabolic heat can also be viewed as an adaptive action, occurring either changing one’s metabolic rate, e.g. by moving around as opposed to sitting, or with the consumption of cool drinks to reduce one’s metabolic heat. Once again, even though the correlation is weak (-0.20, p< 0.01), there appears to be a tendency for lower physical activity as air temperature increases. The consumption of cool drinks has been demonstrated to affect the metabolic heat produced, reducing it by 10% [29]. Thus although the consumption of cool drinks is not solely a response to thermal conditions, there are nevertheless increased occurrences of people having cold drinks as air temperature rises (r=0.19, p< 0.01).

Comparing air temperature with physical activities for different cities, on a seasonal basis, using grouped metabolic rates for such comparison, provides interesting results. Metabolic rates were calculated according to ISO 7730 [27] using data collected from the interviews, through observations of activities. The majority of the people interviewed had a relatively low metabolic rate, of around 1 met, sitting, or slightly higher standing up, etc. To compare metabolic rates and air temperatures on an equal basis, i.e. ignoring respective frequencies, mean values are employed for the analysis. Overall, there is a tendency for activities of low metabolic rates to be associated with higher air temperatures (Table 6), for each season separately.

The exception to this is people playing sports. Although overall, there were very few people playing sports in the areas under consideration (metabolic rates > 3 met), they have been included in the analysis, demonstrating an interesting point, which is further explained in the Section for psychological adaptation. The few cases of people jogging in Milan, Cambridge and casually playing basketball in Athens demonstrate that the need to carry out their exercise was overriding any thermal discomfort. This is particularly the case of the two teenagers playing basketball in one of the sites in Athens, where a small basket-ball court was available, in the summer, at air temperature of 35.5 °C in the midday sun! Clearly, under such conditions all outdoor activities are limited to the mere necessary and seeking shade is the norm. However, in this case the need to play basket-ball was far greater than any thermal discomfort experienced, and the increased thermal load to the body was not considered an issue.

Table 6: Seasonal analysis of mean air temperature (°C), for grouped metabolic rate (met) for the different cities and for the whole database

Season	Grouped met rate	Athens	Cambridge	Fribourg	Kassel	Milan	Sheffield	Thessaloniki	Overall Mean
Autumn	1	18.9	8.8	11.8	16.7	14.5	16.8	9.7	14.0
	2	18.8	9.7	11.6	16.3	13.9	16.5	10.0	13.2
	3			12.8			15.8	9.6	11.3
	4					11.4			11.4
	5					15.8			15.8
Spring	1	22.1	23.3	14.9	22.8	23.3	12.9	21.5	20.3
	2	20.9	21.5	13.7	20.9	24.4	14.3	20.8	17.4
	3			12.8			12.4	22.2	18.5
	5		20.8						20.8
Summer	1	30.1	23.5	24.4	22.6	26.2	20.9	26.3	25.5
	2	29.5	21.4	22.6	20.9	27.2	21.9	26.6	23.9
	3	31.6		25.0		29.0	21.6	24.8	25.6
	5	35.5	21.4						28.4
Winter	1	16.4	10.9	7.7	6.2	11.0	9.5	15.5	12.9
	2	16.2	10.9	6.5	5.3	10.1	9.2	15.0	9.9
	3			7.9			11.4	13.1	9.8

3.4.2 Psychological adaptation

Psychologically, personal choice, memory and expectations prove to be critical parameters for satisfaction with the thermal environment.

The immediate effect of expectations is evident through anecdotal comments, such as “it’s OK for this time of year”, “it’s the summer what do you expect”, etc. Expectations, however, are affected by short-term experience, which is related to memory and seems to be responsible for the changes in people’s expectations from one day to the following.

In relation to thermal sensation, expectations are most probably responsible for the very small amount of extreme votes (±2) under a very wide range of climatic conditions, across Europe, throughout the year. Similarly, the low percentage of hot discomfort in climates such as Greece and Italy in the summer (Fig. 6) is another indication of the influence of psychological adaptation, as in both countries hot summers are expected, people have learned to cope with them and are not seriously affected by them. On the other hand, in Switzerland, summers are normally cooler and as a result thermal discomfort from the heat at the time of the surveys is more prominent; eventhough microclimatic conditions are more favourable than in Italy and Greece for the same season. As Höppe argues, expectation of specific thermal conditions is the major aspect for personal satisfaction [13].

This is also the main reason that neutral temperatures, as have been calculated through probit analysis, appear to follow the profile of the respective climatic temperatures on a seasonal basis, which seems to be the case for all cities. Physical adaptation in the form of seasonal compensation of clothing, consumption of cool drinks and location in space, only partly justify this extended range of neutral conditions. The strongest influence is that of recent experiences and expectations.

The role of recent experience in influencing expectations is also demonstrated through the relevant shift of the comfort zones for different times of the year, as people seem to prefer temperatures which follow the profile of the preceding season (Fig. 8). Thus, warmer temperatures are expected in autumn, following the hot climatic conditions of the summer, whereas in spring, cooler temperatures are regarded as comfortable, following the cold conditions of winter.

In summary, the wide neutrality zone found across Europe can be viewed as a result of adaptation, particularly in view of people’s thermal experiences and expectations. This is primarily responsible for the respective differences, between southern and northern latitudes, where higher neutral temperatures are found for the former and lower for the latter (Table 5).

Perceived control over a source of discomfort in the outdoor context is demonstrated with the choice of sitting in the sun or shade, as well as with the opportunity to leave the area when the thermal comfort conditions become unbearable, i.e. primarily through personal choice for being in the area.

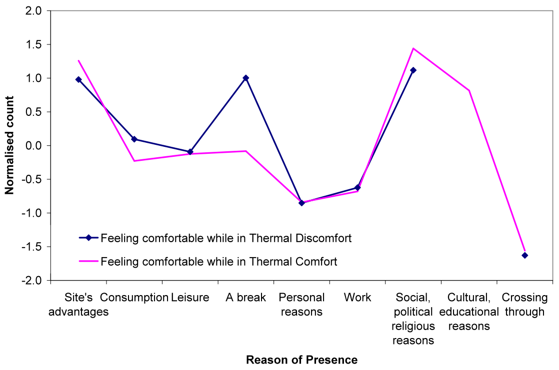
This choice can be implicit in the actions and reasons for being in the space, to the extent that people may not even be aware of its importance. To demonstrate this importance, the reasons people mention that brought them in the area have been analysed in relation to their comfort state. In order to analyse the different reasons for people being in the space on an equal basis, irrespective of the actual number of responses, these were normalised. Only people being in overall comfort state were considered and split into two groups with respect to thermal comfort/discomfort. Normalised counts have been calculated for each group, by subtracting from each category count the average of the respective thermal sensation group and dividing by the group’s standard deviation. (Fig. 13).

It became apparent that the amount of people feeling comfortable while in thermal discomfort was lower when the only reason for being there was for work or other personal reasons which were not related to a desire to be in the space, but e.g. to meet someone. Similarly, discomfort is less tolerated when people were just crossing through the area, en route to somewhere else, as opposed to seeing the open space as their destination.

This is due to the fact that people who are in the space by their own choice, rather than it being compulsory, have decided to expose themselves to these conditions and can terminate such exposure when the thermal environment becomes a source of discomfort simply by leaving, therefore are more tolerant to the thermal environment. This, which is in accordance to a previous study on the UK climatic context [2, 14], finds wide application across Europe, irrespective of personal characteristics and cross-cultural differences.

The important role of cognition can also be demonstrated, examining thermal discomfort in the overall comfort state. In Figure 13, there is a category for people being in the space in order to have “a break”, e.g. from their work. It is interesting to notice that despite the fact that a significant proportion is in thermal discomfort, they have reported feeling comfortable. This shows that the need for environmental stimulation is greater than the limited experience of thermal discomfort, which they are prepared to accommodate, thus excessive stress is avoided.

In the framework of the social analysis carried out within the project, information was also obtained during the interviews on whether people were there by themselves, accompanying others, or merely with a dog, which in most cases translated to take the dog out for a walk. Plotting such information, against the normalised count of people being in overall comfort state, once again provides interesting information (Fig. 14). The percentage of people being in overall comfort is quite low for those that are there with a dog and the relative tolerance of thermal discomfort very limited. This can be explained, if walking the dog is seen as a duty which has to be carried out, as opposed to a desire to be in the space. Exposure to the thermal environment can only be terminated once the duty has been carried out, thus discomfort is increased.



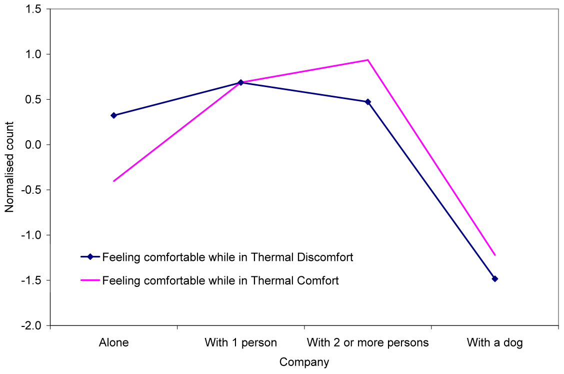


Figure 13: Normalised count of people being in comfort for the different reasons that have brought them in the space (left)

Figure 14: Normalised count of people being in comfort according to the company they have in the space (right)

To summarise, it is apparent that people who are in the space by their own choice and as such have decided to expose themselves to these conditions, which can terminate by simply leaving, become more tolerant to the thermal environment. However, people that were not there by their own choice but to meet someone, or perform a duty instead, did not have the option of leaving when they wished so. The termination of their exposure to the thermal conditions was dependent on external factors, e.g. the arrival of the other person, upon finishing their work, or other duty they had to carry out, which was causing distress, making them less tolerant to the environment.

In this context, the irrational –in terms of thermal load on the body– act of two teenagers playing basketball in Athens in the summer in the midday sun, at an air temperature of 35.5 °C, can be justified. The desire to play basket-ball was clearly far greater than the thermal discomfort experienced, and the increased thermal load to the body was sustained for a little while, as they were aware that this was their own choice and could be terminated whenever they desired.

This issue of free choice becomes of prime importance in outdoor spaces, where actual control over the microclimate is minimal, perceived control having the biggest weighting.

Conclusions

The work described in this paper presented some of the findings of an extensive European project, RUROS, primarily concerned with the environmental and comfort conditions of open spaces in cities. Field surveys in 14 different case study sites, across 5 different countries in Europe provided the spine of the research. The results of the microclimatic and human monitoring of nearly 10,000 interviews, in relation to the thermal environment and comfort conditions in open spaces have been presented.

The findings confirm that there is a strong relationship between microclimatic and comfort conditions, with air temperature and solar radiation being important determinants of comfort, although one parameter alone is not sufficient for the assessment of thermal comfort conditions. Regarding the wind, there is increasing discomfort as wind speed increases, depending on air temperature, as at high air temperatures the cooling effect of the wind is desired.

In relation to comfort, the majority of the people found outside have reported feeling comfortable, exceeding 75% for all cities on a yearly basis. Sources of discomfort include strong wind at northern climates and stale conditions for air temperatures over 30 °C. Regarding humidity, people are not very good at judging changes in humidity levels, unless relative humidity is very high or very low and normally in conjunction with temperature conditions, indicating a significant second-role for relative humidity in the overall comfort sensation. As expected, thermal sensation of extreme “very hot” and “very cold” votes are associated with increased levels of discomfort, with the higher frequency of +2 and -2 votes found in the summer and winter respectively. In fact, 90% of the population that has participated in the surveys for each country has voted within the $-1 \le ASV \le +1$ zone, despite the great variation of the microclimatic conditions.

Investigating neutral temperatures, i.e. the temperatures where people feel neither warm nor cool, showed a great variation across Europe, of over 10 °C, just below, 23 °C for Athens and 13 °C for Fribourg. The centre values of the neutrality zones present a shift, with the autumn comfort zone found at higher neutral temperatures than spring.

Transitional seasons have wider neutrality zones for southern cities, such as Thessaloniki, yet this difference is minimised for northern cities, such as Fribourg. This could be attributed to the difference in behaviour between the southern and the northern cities, a result of experience to a different range of climatic conditions and difference in sensitivity to heat and cold. This sensitivity to cold is also apparent when comparing the neutral temperatures with the respective long term climatic temperatures for the different cities. Neutral temperatures appear to follow the profile of the respective climatic temperatures on a seasonal basis, while the difference between the two is inversely proportional to the climatic air temperature; hence, in the summer the two sets of temperature lie very close, while the biggest difference is noticed in winter. Thus, people have the required mechanisms to adapt more easily in the heat, whereas this sensitivity to cold could provide an early warning for the subject to react and prevent further cooling of the organism, which would be hazardous.

Furthermore, it has been shown that there is strong evidence of adaptation taking place, both physically and psychologically. Physically, this is apparent with the seasonal variation in clothing and changes to the metabolic rate, with a tendency for activities of low metabolic rates to be associated with higher air temperatures. However, such actions are not sufficient to allow for the great variation in thermal neutrality. Recent experience and expectations play a major role and are responsible for the fact that neutrality in autumn and spring follows the behaviour of the preceding season. In this context, warmer temperatures are expected in autumn, following the hot climatic conditions of the summer, whereas in spring, cooler temperatures are regarded as comfortable, following the cold conditions of winter.

Another important parameter of psychological adaptation becoming apparent is the perceived choice individuals have over a source of discomfort, when visiting an open space. This can include different aspects, from choice of sitting to avoid discomfort, to being in the area by one's own choice, as opposed for duties which render presence compulsory. The difference between the last two is that people in the area who have decided to expose themselves to certain conditions by their own choice are more tolerant to the thermal environment, as they can terminate such exposure by leaving, as opposed to being dependent on external factors.

Adaptation procedures can enhance the use and experience of open spaces in the city fabric. However, it is important to stress that they are not to be used as an excuse for the absence of climatic analysis on such basis. On the contrary, the strong relationship between microclimatic and comfort conditions and need for environmental stimulation demonstrate that careful design can allow for the use of open spaces, even at relative harsh microclimatic conditions, whether from heat or cold, balancing exposure and protection to the different climatic elements. However, this can only be feasible, if great care is taken to include microclimatic concerns at the design phase.

Finally, based on the large database collected it will be possible to proceed and develop appropriate models for the prediction of thermal comfort conditions in the outdoor context, using readily available data, taking into account intrinsic personal parameters, as opposed to the human thermoregulatory system alone.

This would assist the design of cities through the design of outdoor spaces and eventually the use of these spaces, by allowing for different activities to be carried out and social interaction to take place, giving life back to the cities' open spaces. Ultimately, such systematic knowledge can contribute to the sustainable development of cities of the future.

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