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Outdoor thermal comfort

Marialena Nikolopoulou

University of Bath, Department of Architecture and Civil Engineering, Bath BA2 7AY, UK

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1. ABSTRACT

A review of the various approaches in understanding outdoor thermal comfort is presented. The emphasis on field surveys from around the world, particularly across Europe, enables us to understand thermal perception and evaluate outdoor thermal comfort conditions. The consistent low correlations between objective microclimatic variables, subjective thermal sensation and comfort outdoors, internationally, suggest that thermophysiology alone does not adequate describe these relationships. Focusing on the concept of adaptation, it tries to explain how this influences outdoor comfort, enabling us to inhabit and get satisfaction from outdoor spaces throughout the year. Beyond acclimatization and behavioral adaptation, through adjustments in clothing and changes to the metabolic heat, psychological adaptation plays a critical role to ensure thermal comfort and satisfaction with the outdoor environment. Such parameters include recent experiences and expectations; personal choice and perceived control, more important than whether that control is actually exercised; and the need for positive environmental stimulation suggesting that thermal neutrality is not a pre-requisite for thermal comfort. Ultimately, enhancing environmental diversity can influence thermal perception and experience of open spaces.

2. INTRODUCTION

Writing a paper on outdoor thermal comfort for a journal in bioscience, with a background in architecture-engineering is a challenging task. It is not just the focus of attention that is different, interactions between humans and the built environment, as opposed to functions within the human body, but also differences in semantics, scale and scientific language. Despite the initial hurdles, there is a common aim to improve the fit between the human organism and the immediate environment.

In fact this area can be an intersection of various scientific fields, each one looking at it from a different perspective, highlighting the complementarity of the various approaches. On one hand, we have physiology, psychobiology, behavioral ecology and other natural sciences. On the other hand we have engineers, climatologists, biometeorologists, geographers and architects focusing on the physical environment and the interactions with the human body. In what could appear as a dichotomy of approaches, it can be easily appreciated that none of the above is a closed system and additionally the field of psychology offers synergies and helps to further explain various processes. It may very well be that "the interface between physiology and psychology remains largely terra incognita" (1), nevertheless, there is an increased amount of research in behavior and how it becomes integral to enhance 'survival'.

So what is actually meant by *outdoor thermal comfort*? If we first look at available definitions for *thermal comfort*, we notice that this can be rather vague. The American Society for Heating, Refrigerating and Air-conditioning Engineers define it as a 'state of mind that expresses satisfaction with the thermal surroundings' (2), a rather diverse definition, particularly so for an engineering body. As Heijs (3) argues, it does not say what state of mind that is (in terms of perception, feeling, etc.), provides no indication of how to relate this mental state into something that can be measured, and the variables involved are not clear. Subjective parameters are "prominent by their omission" (4). This complexity explains the extensive research, of different approaches, in the field.

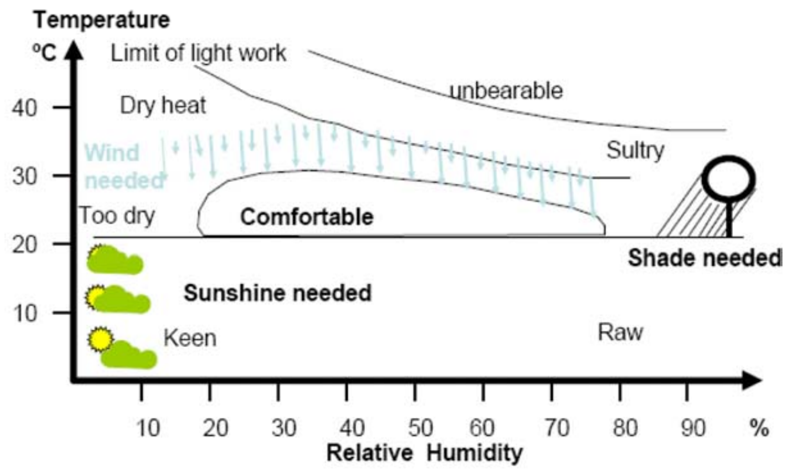

Figure 1. The Olgyay bioclimatic chart (11) (adapted with permission by Martin Wilkinson, University of Bath)

If we consider thermal comfort in the outdoor environment, with the added complexity of the wide spatial and temporal variability of environmental conditions, the interactions between the physical environment, as well as physiological and psychological mechanisms become even more challenging. It is discussions around sustainable urban environments, the sometimes inhospitable developments in city centers, along with the increasing importance of open spaces under climate change that have brought *outdoor thermal comfort* to the forefront.

Given the wide audience interested in the field, this paper initially provides a brief review of the various approaches in understanding outdoor thermal comfort, through physiology with the development of thermal indices. It then examines field surveys concerned with people in the real world, to enable us to understand thermal perception and evaluation of outdoor thermal comfort. Finally, it focuses on the concept of adaptation in the wider context and tries to explain how this influences outdoor comfort, enabling us to inhabit and get satisfaction from outdoor spaces throughout the year.

3. APPROACHES TO OUTDOOR THERMAL COMFORT

3.1. The physiological approach

For the proper functioning of the human body, a constant deep core temperature of around 37 ºC must be maintained; balancing heat gains and heat losses from the surrounding environments as well as basal metabolic rate. This basic heat balance equation describing the thermal exchange between the human body and the surrounding environment has formed the basis for current thermal standards, following the physiological responses of the human body (2, 5).

Air and mean radiant temperature, air movement and humidity are the basic environmental parameters affecting the thermal environment and consequently thermal comfort. Behavioral actions such as clothing and metabolic activity, with the respective energy production, are considered as additional parameters to describe alterations to the system, influencing the process where heat is generated in the body and dissipated to the environment.

The physiology of thermal comfort in the outdoor context has been described in a similar way with an important additional climatic variable to indoor spaces; solar radiation. To evaluate the thermal load people are exposed to, over 100 thermal comfort and thermal stress indices have been developed either empirically, or based on energy budget models, which have become increasingly sophisticated over the years. These indices have been employed as indicators for public weather services, warning systems, urban planning or ergonomic advice, etc.

One of the earliest and most widely used indices has been the original windchill index to take into account the cooling effects of wind (6). This index has been widely used in weather forecasts for the general public and adapted (7-8), particularly in countries with severe cold weather. Its widespread use for decades even prompted a Windchill Workshop over the internet in 2000, to provide a basis for making improvements to the windchill program (9). At the other end of the spectrum, a popular empirical index for warm-humid climates is the discomfort index (DI) also known as temperature-humidity index (THI) developed by Thom (10).

In the mean time, designers in the urban environment became interested in thermal comfort as a means to improve design of spaces. Olgyay (11) combined the effects of different climatic elements, including solar radiation figures which were to be used for outdoor conditions, in what was defined as the "bioclimatic chart" (Figure 1).

Penwarden (12) also added a term for solar radiation to the heat balance model of the human body used indoors, to calculate thermal comfort conditions. Advancement over previous models and the Olgyay chart (11) was that he included different clothing insulation values. Two different comfort charts are presented for strolling in full sun and shade, where the combined effects of sun and shade with air temperature, wind and different clothing levels can be examined, with categories for just sweating, comfortable and just shivering. Later still, comfort criteria were further suggested by Arens and Bosselmann (13), who carried out extensive work to improve microclimatic conditions at downtown San Francisco (14) and Toronto (15).

Popular indices for the outdoor thermal environment include COMFA and OUT_SET. COMFA (16) was developed for use in the field of landscape architecture to evaluate different landscapes and the influence of solar radiation and vegetation (17). The Outdoor Standard Effective Temperature (OUT_SET*), developed by Pickup and de Dear (18), is an adaptation of Gagge's classic indoor climate index SET (19), integrating a model for the radiant environment outdoors. It was also used experimentally for heat stress and thermal comfort forecasts predominantly in Australia for the Sydney 2000 Olympics (20).

One of the most popular indices developed for the outdoor context was the Physiological Equivalent Temperature, PET, based on an energy balance model of the human physiology (21). As PET uses ºC for its unit, it is more comprehensible by professionals other than biometeorologists, such as planners, and for that it has been widely used. Since its development it has been employed as a universal thermal index (22) and has been applied extensively for assessing thermal environments. It has been used in modeling studies, evaluating the effect of geometry and other design related parameters on outdoor thermal comfort (23-26), while it has been integrated as an index in software models evaluating outdoor thermal comfort conditions, such as RayMan (27-28) and the three-dimensional ENVI-MET (29).

The most extensively used index, which worryingly has been popular for the outdoor context, is the Predicted Mean Vote, PMV (30). PMV was developed specifically for indoor environments, based on extensive controlled experiments with human subjects sitting in climate chambers. PMV has been adopted by various standards for specifying indoor thermal comfort conditions (2, 5, 31). Due to the dynamic and unstable conditions found outdoors, the PMV cannot be used outdoors in its original form hence should not be employed beyond the context for which it was originally developed (32). There have been various attempts to use the PMV model in the outdoor context, through parameterization of the complex radiation fluxes, the most popular being the Klima-Michel-Modell developed by Jendritzky specifically for outdoor use (33).

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An important limitation of most thermal indices, including PET is that they are all based on steady-state energy balance models of the human body. Yet people outdoors rarely experience thermal balance, hence the steady-state approach is insufficient (34). In response to that, the Universal Thermal Comfort Index, UTCI, has been developed which was released in the summer of 2009, as a result of COST Action 730 (35). UTCI is based on Fiala's dynamic 340-node model (36), allowing calculations of the thermal state of different parts of the human body.

It is apparent that we now have a range of tools evaluating outdoor thermal comfort at varying degree of sophistication, simulating the anatomical, thermal and physiological properties of the human body.

However, in this process we have distanced humans from the real world context. The same way that studies in climate chambers distanced people from real buildings, which led to the debate between conventional and adaptive thermal comfort conditions (37-38) and eventually led to adaptive comfort standards (39-47), we are facing a similar if not wider divergence in the outdoor context. Such a debate can be critical when the focus is on the design of open spaces for sustainable urban environments with the wider implications under climate change.

Without diminishing the importance of the thermoregulatory system in the process of achieving thermal comfort in the outdoor context, we need to look beyond thermal physiology to enhance our understanding of the discrepancy between actual and modelled data. As Cabanac (48) highlights, the living being is not a "closed system". Indeed, behavioral and other cognitive factors may enrich our understanding of the field.

3.2. Field studies

The majority of the work in outdoor thermal comfort was focused on theoretical thermoregulatory models, with a lack of understanding of the more subjective human parameter. This realization eventually led to an increased number of field surveys around the world, at different geographic and climatic contexts. These have been viewed as indispensable to evaluate outdoor thermal comfort more holistically.

Environmental physiologists and psychologists have been researching the role of behavior in modifying the thermal environment people experience for a number of years, with a number of comprehensive reviews presented in a two-volume collection on Environmental Physiology for the handbook of Physiology by Fregly and Blatteis (49). Interestingly, however, it was initially the field of planning and architecture that focused on field surveys, with the aim of improving the design of urban environments.

In the 1980s a team of researchers at Berkeley (50) introduced the subjective human response, with the aim of providing a broader perspective from which to view thermal comfort in urban spaces. They carried out field surveys in two different spaces in San Francisco, a weekday twice a month, from February to July 1986. Aiming to evaluate people's comfort conditions outdoors, 322 structured interviews were carried out, while a moveable weather station recorded the microclimate at different points around the sites.

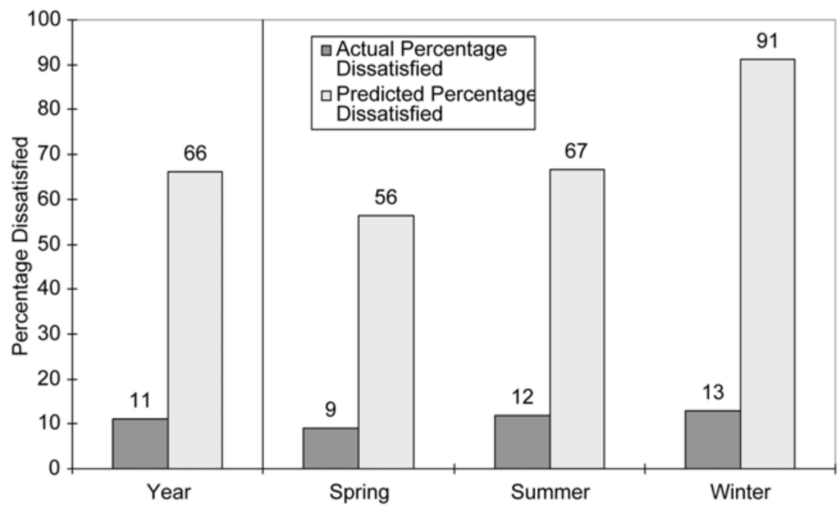

Figure 2. Comparison between Actual Percentage Dissatisfied and Predicted Percentage Dissatisfied, based on 1431 questionnaire guided interviews in Cambridge UK. Reproduced with permission from (51)

A decade later, Nikolopoulou, at the Martin Centre for Architectural and Urban Studies in Cambridge (UK), interviewed 1453 users of four different sites in the city center at different seasons from 1996 to 1997 (51). Microclimatic parameters were monitored using a portable mini weather as the interviews were carried out.

Both of these studies revealed close relationships between comfort and environmental parameters, which also influence the use of space. Furthermore, the Cambridge study highlighted the great discrepancy between theoretical thermoregulatory models and subjective human responses (51). The theoretical Predicted Percentage of Dissatisfied, PPD, (5), based on the PMV model, varied from 56% in spring to 91% in winter, with a yearly average of 66% (Figure 2), implying that 944 of the 1431 people who participated in the surveys should be dissatisfied with their thermal environment. However, the Actual Percentage of Dissatisfied was always around 10%, a figure that is regarded as acceptable, even in controlled indoor environments. They also highlighted that thermal variables typically account for only half of the variation in the thermal sensation. This suggested that a purely physiological approach was inadequate in characterizing outdoor thermal comfort conditions.

In the last 10 years, field studies investigating outdoor thermal comfort have also taken place around the world; Japan and Israel (52), Canada (53-55), Sweden (56-57), Netherlands (58), Portugal (59), Brazil (60), Australia (61), New Zealand (62), UK (63-65), Bangladesh (66), Hong-Kong (67), Philipinnes (68), Taiwan (69). Amongst various independent objectives, they all focused on evaluating the relationships between outdoor thermal comfort and microclimatic parameters in different climatic contexts. As would be expected, the influence of different climatic parameters varies according to the climatic context, but all the studies highlighted the complexity in determining the relationships between environmental variables and thermal comfort. Furthermore, a common finding from all the surveys concerned the wide range of comfort zones experienced; significantly wider than would be defined by theoretical models, strengthening the argument for thermal adaptation.

These aspects were investigated in detail in the most extensive study of outdoor thermal comfort to date, project RUROS: Rediscovering the Urban Realm and Open Spaces (70). RUROS included field surveys in seven cities across Europe, encapsulating the large geographic, climatic and cultural variation encountered. The cities involved in the project were Athens (37ºN, 23ºE) and Thessaloniki (40ºN, 22ºE) in Greece, Milan (45ºN, 9ºE) in Italy, Fribourg (46ºN, 7ºE) in Switzerland, Kassel (51ºN, 9ºE) in Germany, Cambridge (52ºN, 0ºE) and Sheffield (53ºN, 1ºE) in the UK. Two case study sites were investigated in each city, for a week each, in the different seasons. The surveys comprised 9189 questionnaire guided interviews with users of the different open spaces, while a portable weather station was monitoring the resulting microclimate (71)

The project enabled to study the impact of environmental stimuli on the use of space (72) and people's thermal sensation and comfort evaluation (71), along with the development of simplified comfort models (73-74). However, it is thermal sensation and the issue of thermal adaptation that is the focus here.

4. THERMAL SENSATION AND COMFORT

Due the great geographic distribution of the RUROS cities, there was a wide range of climatic data encountered in the different seasons. The highest mean air temperature in the summer was recorded in Athens (30.1 °C) and the lowest in Sheffield (21.3 °C). In winter, the highest mean air temperature was in Athens (16.4 °C), although in Thessaloniki it was cooler in autumn (9.9 °C), and lowest in Kassel (5.4 °C).

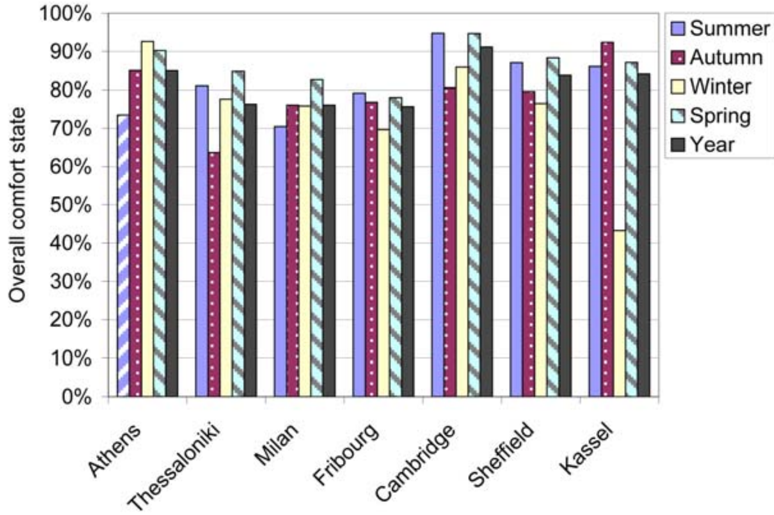

Figure 3. Percentage distribution of overall comfort state, for the different cities, at different seasons. Reproduced with permission from (71). During the interviews, people's thermal sensation was reported on a 5-point scale, varying from "very cold" (-2) to "very hot" (+2). This was defined as the Actual Sensation Vote (ASV). The combination of air temperature and the radiant effect of the sun have the biggest influence on ASV, as the various correlations between ASV and microclimatic parameters demonstrated. In fact Pearson correlation coefficient (r) between ASV and globe temperature is 0.53, whereas when compared with air temperature alone, r = 0.43 (all at $p<0.01$). The relatively weak correlations between microclimatic variables and ASV indicate that one parameter alone is not sufficient for the assessment of thermal comfort conditions.

Despite this variation, the levels of overall comfort are very high for all cities and seasons (Figure 3), demonstrating that in the vast majority people is satisfied with the environment (71). In fact, overall comfort on an annual 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 (71).

As in general, thermal discomfort is closely associated with the extreme ±2 categories for 'very cold/hot', it is worth investigating closely the conditions for the people that have voted in the region of $-1 \leq ASV \leq +1$, broadly associated with thermal comfort. Around 90% of the votes of the population that has participated in the surveys for each country lie in this zone (Figure 3) (71), consistent with the results of the previous study in Cambridge (51).

Examining the aggregate RUROS dataset (71), only 4% of the interviewees have reported to be feeling "very hot" (+2) and another 4% "very cold" (-2), figures regarded as acceptable even in the tightly controlled indoor environment. The majority of the votes correspond to 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) (Figure 4). Even more interesting, in the UK (1956 interviews), 39% of the population has reported feeling "warm", with neutrality votes following with 27%. As expected, a shift towards cooler votes occurs, moving from summer to spring / autumn and finally winter.

4.1. Neutral temperatures

Investigating the temperature zones of thermal neutrality, i.e., where people feel neither warm, nor cool, is an interesting ways of examining thermal sensation. Thermal neutrality zones were calculated using probit analysis (75), 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 obtaining temperatures where, for instance.50%, of the interviewees would be in the verge of changing their ASV to the next higher value. Neutrality zones were determined for each city on an annual as well as seasonal basis. Table 1 presents the center values for these neutrality zones at the level of 50% probability of transition, which are referred to as neutral temperatures.

A variation of neutral temperature of over 10 K is noticeable across Europe. 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. Looking at the seasonal analysis and the relevant transition curves, for instance for Thessaloniki (Figure 5), demonstrates how wide the neutrality zones are. The comfort zone for spring and autumn is as wide as 17.6 K and 13.5 K respectively, whereas for summer and winter, it is 5.9 K and 9.6 K wide (Figure 5). The shift of the center values means that the autumn comfort zone is found at higher neutral temperatures than spring, 24.7 °C as opposed

Table 1. Neutral temperature (°C) (center value of the probit neutrality zone at the 50% probability of transition level, for the different cities at different seasons. Reproduced with permission from (71)

	Annual	**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.

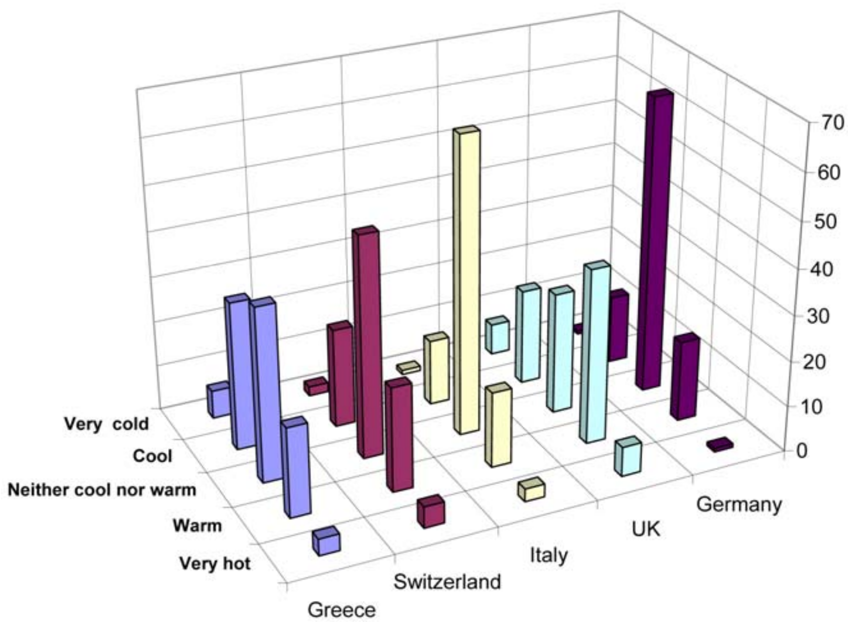

Figure 4. Percentage distribution of the Actual Sensation Vote of the interviewees (ASV) throughout the year, for the different countries. Reproduced with permission from (71).

to 18.4 °C. For winter and summer these values reach more extreme values at 15.0 °C and 28.9 °C respectively.

Interestingly, both autumn and spring appear to follow the behavior of the preceding season. 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. The reasons for the shifting profiles are explained in Section 5.3.2.

Another issue arises from comparing the neutral temperatures with the respective long term climatic temperatures for the different cities (Figure 6). In all cities, neutral temperatures appear to follow the profile of the respective climatic temperatures on a seasonal basis. 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 (71).

The difference between neutral temperature and climatic air temperature appears to be inversely proportional to the mean climatic air temperature of the region (Figure 6). Hence, as climatic air temperature increases, the closer neutral temperature is to it, as is the case of summer. This sensitivity to the cold has been documented extensively in physiology and partly explains why humans demonstrate great ability for acclimatization in the heat, as opposed to the cold (76). It is our basic need to defend against the cold that has been a driving force in our evolution process (77).

5. ADAPTATION

So how does the concept of adaptation relate to outdoor thermal comfort? Furthermore, how is adaptation actually defined in this context?

Although some researchers define adaptation in the context of natural selection, focusing on genetic effects (78), here we adopt the wider definition, i.e., the gradual decrease of the organism’s response to repeated exposure to

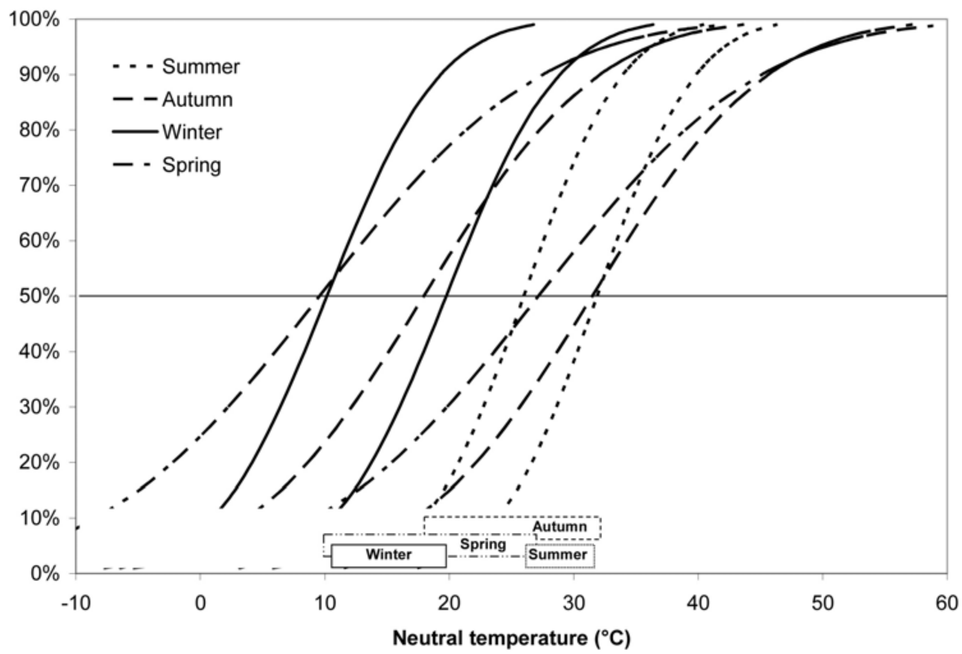

Figure 5. Percentage distribution of change of neutral temperature (°C) to shift from cool to neutral and from neutral to warm for Thessaloniki. Width of comfort zone for the different seasons is transposed at the bottom of the chart. Reproduced with permission from (71).

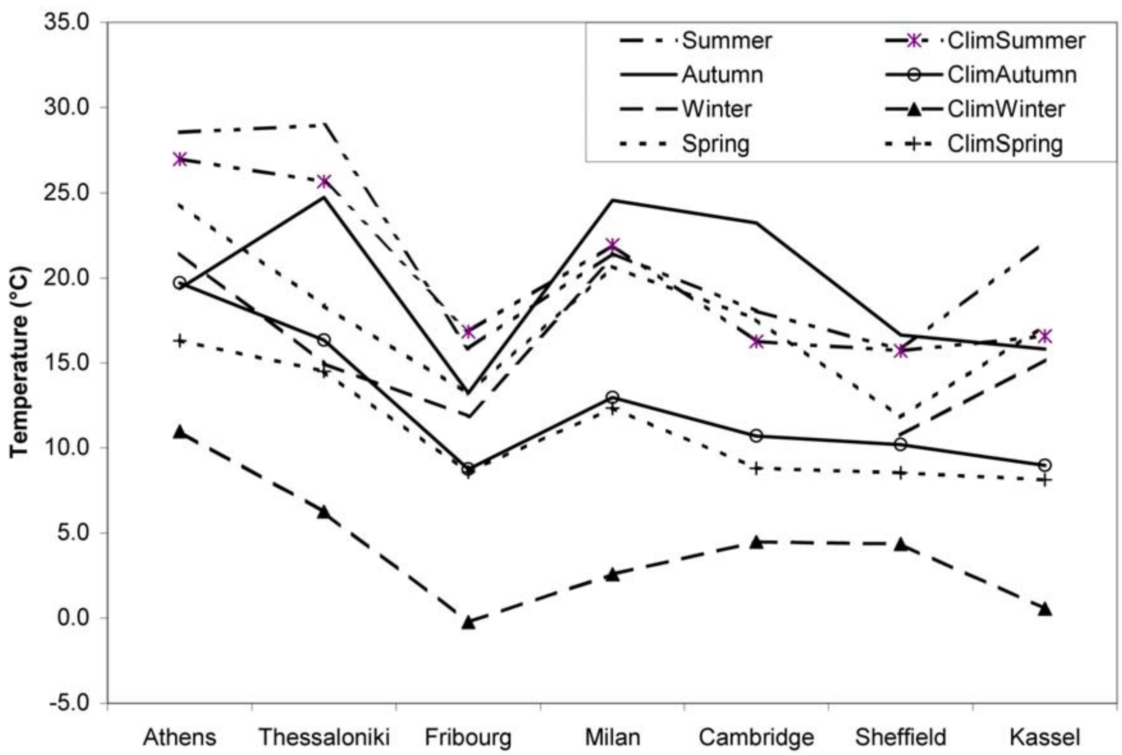

Figure 6. Neutral temperatures compared with the relevant climatic air temperature for different seasons, for the different cities. Reproduced with permission from (71).

a stimulus, involving all the actions that make them better suited to survive in such an environment. In the context of the thermal environment this can be more focused as “the ability to cope with changes that interfere with the homeostatic of an organism” (79).

To enhance adaptation and hence survival, physiological and behavioral actions are integrated (80). In the case of thermal comfort, it could go further to include psychological factors influencing the thermal perception of a space and the changes occurring in. As Brager and de Dear argue “comfort is not just an outcome of the physical environment (…) it is a complex perception (…) built out of the intersection between objective stimuli with cognitive and emotional processes” (81, p.179).

The following sections focus mostly on physical and psychological adaptation, which becomes very important in outdoor thermal comfort.

5.1. Physiological adaptation

Physiological adaptation or acclimatization has been documented extensively in physiology (49, 82-83). In relation to the thermal environment it involves all the physiological processes and thermoregulatory responses to ensure adaptation in a wide range of hot and cold environments. These changes in the physiological responses result from repeated exposure to a stimulus, leading to a gradual decreased strain from such exposure.

Although overall it is a critical mechanism for humans to ensure survival, in the current context it is not of central importance. In urban centers, particularly in the cities investigated in the RUROS project, people have not exposed themselves to either extreme conditions or for prolonged periods of time for acclimatization to take place. At most, it is the peripheral skin temperature that would vary; which in most cases would be followed by other forms of adaptation as described below.

5.2. Behavioral or physical adaptation

As Satinoff (77) argues most thermoregulation is behavioral, to prevent people getting too hot or too cold or start shivering, etc. In framework of the built environment, Nikolopoulou *et al.* (84) defined physical adaptation in terms of the changes a person makes, 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.

Beyond building shelters to create favorable microclimates, or using technological development such as heating or cooling systems to improve thermal comfort, in the outdoor comfort there is a limited degree of interaction humans can have with the environment. Such actions refer to opening a parasol to provide shade, with more recent examples including the energy intensive outdoor patio-heaters, or outdoor sprinklers for cooling.

Reactive adaptation on the other hand has been key to our species’ survival. Basking in the sun, varying posture to enhance or protect solar or wind exposure for heating or cooling are key behaviors to improve the fit between the environment and our needs. Similarly, it is possible to change one’s activity levels and metabolic rate, whether it involves a brisk walk on a chilly day or limiting physical activity in hotter environments. In fact empirical evidence has shown that humans choose to rest at high ambient temperatures. At the other end of the spectrum, when people were placed in cool conditions and could chose the intensity of muscular work, they adjusted the latter to their own temperature avoiding hyperthermia or hypothermia (1).

In the context of outdoor thermal comfort, spatial variation, by changing one’s position, is an effective way to avoid discomfort, and strongly depends on microclimatic conditions. In a study in the UK, 43% of the variation of people sitting in shade was attributed to air temperature (85). More recently, in a study in Taiwan seeking shade under a tree was the most popular response in dealing with the heat (69).

One of the most common reactive adaptive actions is the variation of clothing. In the RUROS dataset across Europe, the clothing levels of the interviewees were determined using the ISO 7730 values (5). The correlation between air temperature and clothing insulation levels is -0.61 ($p < 0.01$), with clothing insulation reducing as air temperature rises. Examining clothing insulation as a function of mean air temperature, demonstrates this strong relationship, irrespective of geographic location (Figure 7).

Further analysis demonstrated that air temperature is the main determinant of clothing insulation with wind becoming significant only at high wind speeds and low air temperatures, where wind speed is the predominant factor. This is in agreement with the results of a recent study in Birmingham, UK (63), which showed that people chose their clothing mainly depending on the air temperature and tended not to consider wind speeds.

This variation in clothing levels becomes more complex when cultural norms are intertwined, as was highlighted in a recent study which compared the hot arid climate of Marrakech in N. Africa 31°N 8°W and Phoenix-Arizona in USA 33°N 112°W (86). Although clothing insulation levels varied between winter and summer for both cities, in Marrakech clothing insulation was consistently higher than Phoenix, even for similar thermal environments, as both genders tend to wear clothes that cover most of their body, according to cultural norms (Figure 8).

Changes to one’s metabolic heat can also be viewed as an adaptive action, either changing one’s metabolic rate, for instance by moving around as opposed to sitting, or with the consumption of cool drinks to reduce one’s metabolic heat. The RUROS dataset confirmed such negative relationships (71) Although the correlation is weak (-0.20, $p < 0.01$), there is a tendency for lower

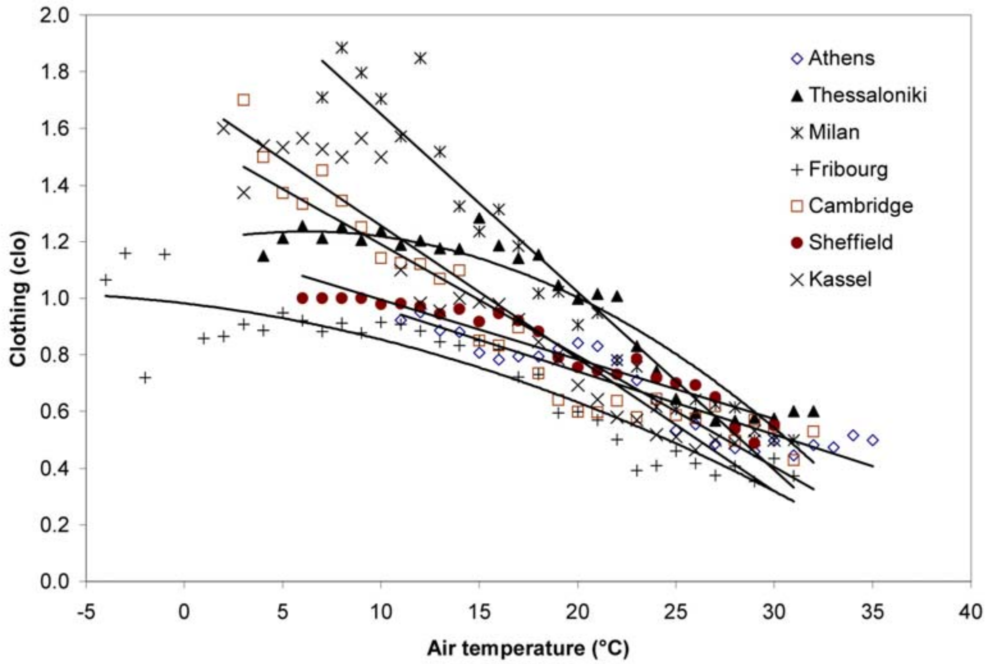

Figure 7. Variation of mean clothing levels (clo) as a function of mean air temperature (°C) for the different cities. Reproduced with permission from (71).

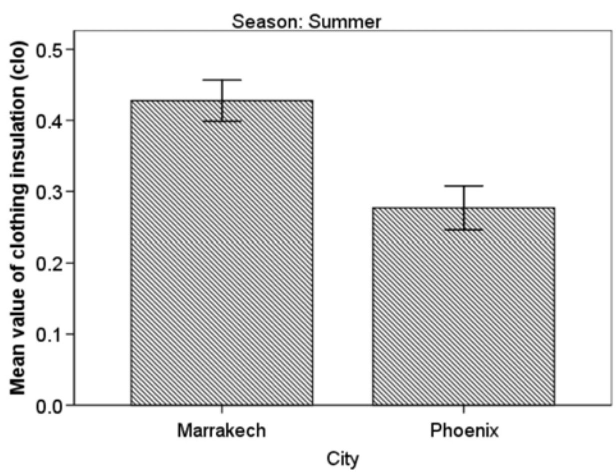

Figure 8. Mean clothing insulation values for Marrakech and Phoenix for the summer. Reproduced with permission from (86).

physical activity as air temperature increases. The consumption of cool drinks has been demonstrated to affect the metabolic heat produced, reducing it by 10% (87). In the earlier field surveys in Cambridge (51), the increased consumption of cool drinks noticed with increasing temperatures was stronger under the presence of sunlight ($r = 0.61$, $p<0.01$). Further work also supports this relationship between cold ingestion and changes in body temperature (1), which also cites studies of penguins ingesting ice when they are overheated. In the all the European cities examined in RUROS, although the consumption of cool drinks is not solely a response to the thermal environment, it nevertheless increased as air temperature rises ($r = 0.19$, $p< 0.01$) helping people to adapt to the thermal conditions.

5.3. Psychological adaptation

The consistent low correlations between objective microclimatic variables and subjective thermal sensation and comfort outdoors, in field surveys across the world, suggest that thermophysiology alone does not adequate describe these relationships; psychological factors also influence the thermal perception of a space. Although the least studied, Brager and de Dear suggest that psychological adaptation could have the most significant role in explaining the differences between actual and predicted thermal sensations (88).

Different people perceive the environment in a different way. Hence 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 therefore influence the thermal perception of a space and the changes occurring in it. Nikolopoulou and Steemers (89) examined a series of parameters (for instance the naturalness of a space, experience and expectations, time of exposure, perceived control and environmental stimulation) that affect outdoor thermal comfort.

Psychologists agree that thermal, emotional and perceptual assessments of a physical place may be intertwined with psychological schema-based and socio-cultural processes (90), and more recently Knez *et al.* (91) referred to the psychology of outdoor place and weather assessment.

So how do psychological factors relate to the findings of field surveys in outdoor thermal to strengthen such arguments?

5.3.1. Environmental stimulation

A starting point would be to enquire the current belief behind current standards that thermal neutrality is a pre-requisite for thermal comfort (32). There is now overwhelming evidence that people enjoy environmental stimulation and a static environment becomes intolerable. "Do people like to feel 'neutral'?" explored the pattern of variation of the ASHRAE desired thermal sensation scale (92). As early as the 1980s in comfort surveys in buildings, McIntyre showed that people voting for the neutral temperatures in warm climates prefer to be cool and people in cold climates prefer to be warm (93). This is in line with recent findings from the hot humid climate of Taiwan, where people's preferred temperature was lower than the neutral temperature (69).

Even psychologists working in environmental physiology now argue that thermoneutrality and thermal comfort are not identical (77).

The importance of environmental stimulation can be better understood not only when considered with the predominant outdoor climate, but also with the dominant internal climate people nowadays spend the majority of their time in. To evaluate this importance, it is interesting to notice the variation of people's actual thermal sensation and thermal preferences in the summer field surveys in Phoenix (86).

Although theoretical models suggest that at the mean air temperature of 39-41 ºC nearly 100% of the people should be in thermal discomfort, it is less than 50% that have voted for very hot (+2) (Figure 9a). More significantly, 25% to 40% of the participants, depending on the site, suggested that they did not want the conditions to change (Figure 9b)! As people spend long periods of time in artificially cooled spaces, due to the widespread use of air-condition in Phoenix, it could be argued that people seek environmental stimulation and hence tolerate significantly higher temperatures.

We only need to look at some of the activities humans consciously seek to appreciate the importance of environmental stimulation. Sunbathing on a beach in the hot summer, saunas and Turkish baths push physiology of the human body to its limit, to the extent of proving fatal if duration to such exposure is prolonged. Positive environmental stimulation, whether it is through exposure to the sunshine, breeze or fresh air, is an important parameter for thermal comfort. Thermal satisfaction may only be achieved through sensation and not thermal neutrality.

This is along the *alliesthesia* concept proposed by Cabanac in the 1970s, which currently receives renewed interest in the context of adaptive thermal comfort (94). Alliesthesia –originating from the Greek words for changed sensation– refers to the fact that any given stimulus can be perceived either as pleasant or unpleasant depending on the internal state of a person (95). This emphasizes the importance of pleasure in motivation for all behaviors (96) and enables trade-offs between different needs (97-98).

5.3.2. Experience and expectations

From the human ecology perspective, past exposure to different conditions is key to establishing adaptation levels to the particular environment (99). Consequently, past experience affects people's evaluation of the thermal environment and subsequent expectations. Studies in psychology also confirmed the influence of long-term memory in guiding and affecting people's expectations towards the weather in the urban environment (90-91, 100).

Anecdotal evidence from the RUROS interviews refers to comments such as "I'm from Australia, I like the heat", "it's always raining in Britain"," it's the summer what do you expect", etc. Beyond simple statements, the analysis of the surveys provides further evidence in support of this argument. Figure 4 presents the distribution of thermal sensation votes for the different countries. Despite the wide range of microclimatic conditions, where mean values across Europe range from 5 ºC in winter to 30 ºC in the summer, there is a very small amount of extreme votes (±2). Furthermore, there are very few hot discomfort votes (+2) in climates such as Greece and Italy in the summer and cold discomfort votes (-2) in Switzerland and Germany.

This is to a great extent due to the influence of experience and expectations, as in the former countries hot summers are expected, while in the latter cold winters is the norm. In both cases people have developed the necessary mechanisms to cope with and are not seriously affected by them. Interestingly, in Switzerland, summers are normally cooler with a mean climatic air temperature of 16.8 ºC. Even though microclimatic conditions are more favorable than in Italy and Greece, there is increased thermal discomfort from the heat (Figure 4). Similarly, in Greece, where winters are warmer, there is increased thermal

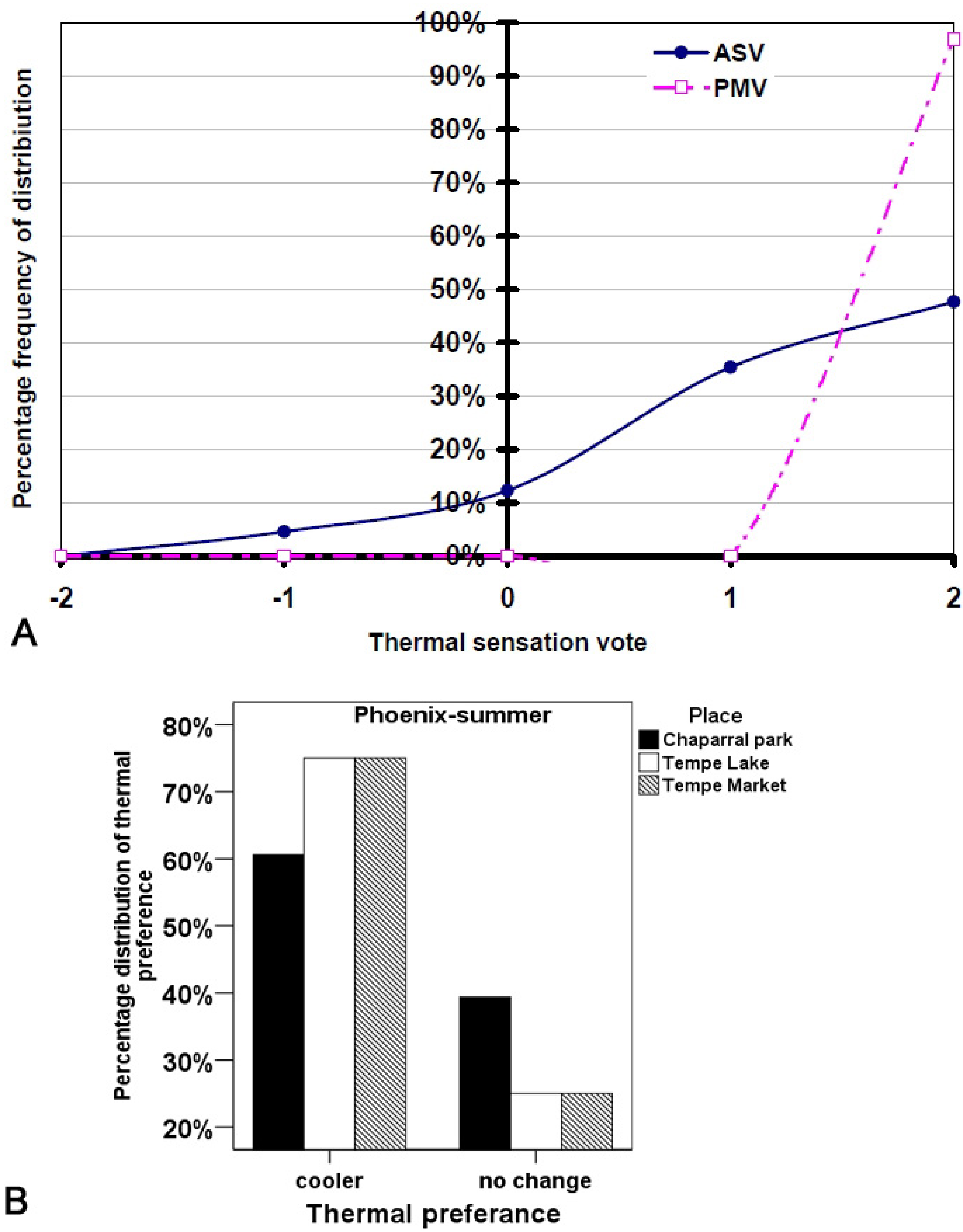

Figure 9. Thermal comfort for Phoenix in the summer (a) Percentage frequency distribution for predicted (PMV) and actual (ASV) thermal sensations; reproduced with permission from (86); (b) Thermal preferences.

discomfort from the cold, despite mean clothing levels being higher than in northern climates (Figure 7).

Overall, the wide neutrality zone found across Europe (Table 1) is significantly affected by people's thermal experiences and expectations, particularly between southern and northern latitudes, where higher neutral temperatures are found for the former and lower for the latter.

Shifting the discussion from comfort to *dis*comfort, we notice parallel trends. The absence of a formal consistent definition to define heat wave episodes, across Europe (101) may be partly due to the influence of thermal experience. Some countries refer to air temperature only, whereas others combine it with humidity, or number of days over a critical temperature, or combination of minimum and maximum daily temperatures, or use thermal indices. Even when only air temperature is used as a criterion for releasing temperature warnings, this varies from 33 ºC in Latvia to 40 ºC in Malta (102). In essence, a definition of a heat wave should meet the criteria that society is susceptible to or unable to cope with these events (103). Hence concepts of adaptation that go beyond thermal physiology and include personal, behavioral, cultural or even societal issues become very important.

Unlike long-term memory, short-term experience affects people's expectations of the space from one day to the following. This becomes more prominent through the seasonal variation of the neutral temperatures, as physical adaptation such as clothing and location in space, etc., can only partially justify this extensive range. Figure 5 demonstrates 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. 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.

This short-term adaptation was also evident in the responses from participants in a pilot summer survey in Israel. The slight cooling experienced in the afternoon, after exposure to severe mid-day heat stress, created the impression of thermal comfort (104). Analyzing the use of space in an urban square in Athens, in the summer, found increased presence of people in the space in the evening. The air temperature of 30˚C after sunset was regarded as relatively cool, when the midday air temperature was 35 ˚C (72).

Recent work in biometeorology has also shown that short-term adaptation can be responsible for the spatial and temporal variation in mortality figures across Europe and suggest the possibility of including short-term adaptation in a heat load warning procedure (103). The relative changes in temperatures are more important than the absolute figures.

5.3.3. Personal choice and perceived control

Personal choice and perceived control is another critical parameter for satisfaction with the thermal environment. This can be implicit in the actions and reasons for bring people in the space. In the majority of cases, it can be argued that people found outdoors in the urban environment, are there by their own choice. Hence they have greater control and can terminate the exposure to the conditions when desired. On the contrary, people who are found outdoors because they have to work, or waiting for a third party to arrive, have a higher probability of being dissatisfied with the environment (71, 89). This is because 'personal choice' is partly absent; they cannot terminate exposure to the thermal environment when desired, as this depends on other parameters, such as work or appearance of the third party.

Other means of control in outdoor spaces can include the greater degree of control of the seating area, as well as the amount and type of clothing worn, as opposed to actual control over the microclimatic parameters. Ultimately, the degree of perceived control is more important than whether that control is actually exercised. Paciuk (105) first suggested this concept of 'perceived control', when she found the positive influence the option and knowledge to take action over a source of discomfort in buildings had on people's thermal satisfaction.

The importance of autonomy was further verified in the hot humid climatic context of Taiwan. People who actively chose to visit the urban square under investigation significantly increased the respondents' tolerance and acceptance of the thermal environment (69).

6. CONCLUSIONS

Humans have depended on their senses for their survival. Yet in the last 50 years, we have tried to eliminate their importance in creating positive sensory experiences. We are regarding any departure from neutrality as a threat in the conquest of creating sterile uniform environments, forgetting that such conditions are virtually non-existent in nature.

This paper has hopefully demonstrated the wide range of outdoor thermal comfort conditions and the crucial effect of adaptation to enhance satisfaction in these places. The extensive field surveys across the world confirm the strong relationships between microclimatic and comfort conditions. However, these environmental parameters only account for about 50% of the variation in thermal comfort. Beyond acclimatization and behavioral adaptation through adjustments in clothing levels, spatial variation and consumption of cool drinks, psychological adaptation plays a critical role to ensure thermal comfort and satisfaction with the outdoor environment.

By no means does the paper suggest disregarding physiological processes and thresholds, as these rules have enhanced survival and prosperity of the human race. But as we are mostly concerned with what Fregly and Blatteis (49) refer to as "optimal zones", it is important to revise the very prescriptive nature of thresholds based on indices developed from energy-balance models. Such models have important shortcomings by disregarding psychological and socio-cultural parameters, which enable people to adapt in a wide range of thermal conditions.

Whether current thermal comfort indices are calibrated to compensate for adaptation in different places (60, 106) or whether psycho-climatic indices (73) need to be developed is a different matter. The knowledge of the complex relationships between psychological adaptation and outdoor thermal comfort should provide guidance, as opposed to precise decision-making tools, to design better spaces. The effect of experience and expectations, the importance of positive environmental stimulation and other personal parameters can enhance environmental diversity and hence the experience of open spaces in the urban fabric.

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Send correspondence to: Marialena Nikolopoulou, University of Bath, Department of Architecture and Civil Engineering, Bath BA2 7AY, UK, Tel: 44 1225 386296, Fax: 44 1225 386691, E-mail: mhnikol@hotmail.com

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