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# Comparison of outdoor comfort field data against calculations of the thermal indices PMV and PET

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## Abstract

We carried out an extensive series of measurements and surveys in a pedestrianized area of Glasgow, UK (55°51'N, 04°12'W) to understand the thermal preferences of local population and to define a preliminary comfort range using selected thermal indices. Nineteen monitoring campaigns were carried out and 763 outdoor comfort surveys were administered to street users. Weather variables were collected using a Davis-Vantage Pro2 weather station, equipped with temperature and humidity sensors, anemometer, pyranometer and a globe thermometer. Concurrent thermal comfort surveys were carried out using an adapted version of ISO 10551. Weather data were post-processed in Rayman and WinComf for obtaining the thermal comfort indices PET and PMV, respectively, allowing comparisons with thermal sensation/preference votes. Analysis of these outcomes point out to the need for simplifications of the original thermal comfort protocol, with no significant effect on the quality of the results obtained.

*Keywords*: outdoor thermal comfort, thermal sensation, preference votes, thermal comfort indices, thermal comfort protocols.

## Introduction

Depending on the background climatic conditions shaded or sunlit open areas resulting from carefully manipulated urban geometry can lead to greater pedestrian use of urban spaces. By means of such modifications, the attractiveness of outdoor spaces can be further enhanced.

A number of studies carried out in the field of outdoor thermal comfort have attempted to explore the links between thermal comfort and urban planning variables. These include psychological and behavioural aspects of the use of outdoor spaces as a function of overall thermal comfort conditions (Nikolopoulou et al., 2001; Nikolopoulou and Steemers, 2003; Thorsson et al., 2004; Knez and Thorsson, 2006; Eliasson et al., 2007); influence of urban canyons on outdoor comfort (Ali-Toudert and Mayer, 2006; Johansson, 2006; Johansson and Emmanuel, 2006); effect of sky view factor (Upmanis and Chen, 1999; Unger, 2004; Svensson, 2004; Souza, 2007;

Krüger et al., 2010) and vegetation (Shashua-Bar and Hoffman, 2000; Picot, 2004). Other studies have attempted to develop guidelines for improvement of outdoor spaces (Givoni, 1998; Chrisomallidou et al., 2004; Katzschner, 2005; Panogopoulos, 2008; Ng, 2009).

A relevant method of assessing preferable outdoor thermal conditions for implementing improvements in urban geometry from such input data, which is adopted in many of the studies cited above, is based on the administration of comfort surveys with the aid of questionnaires. For that purpose, ISO 10551 (ISO 1995) provides five subjective judgement scales aiming at perception, affective assessment (comfort/discomfort) and future preference of the thermal environment. For assessing the thermal perception of the surveyed population ("How do you feel at this precise moment?"), ISO 10551 recommends the use of the 7 or 9-degree bipolar scale with a central point of thermal neutrality. For obtaining their thermal preference ("Please state how you prefer to be now"), a similar scale is used.

The present paper is part of a broader research initiative aiming at understanding the urban heat island effect to enhance urban resilience to local and global climate change in the city of Glasgow, UK. In this paper, data gathered from outdoor comfort surveys, conducted from March through the end of July 2011 are presented. The analysis is based on the quantification of thermal comfort in terms of Physiologically Equivalent Temperature (PET) and Predicted Mean Vote (PMV) for different sets of conditions: 1) from minimal information regarding microclimate, gender, clothing insulation and thermal perception, 2) from microclimate data, personal data (gender, age, height and weight), clothing insulation and thermal perception, 3) from microclimate data, personal data, clothing insulation and a from a combination between thermal perception and thermal preference. Metabolic rate was assumed constant for all interviewees. The inclusion of data such as gender, body mass and age was meant to allow group analysis of the effect of personal data on observed (against predicted) thermal sensation, as discussed in Krüger et al. (2012).

## Outdoor comfort surveys

According to Koeppen-Geiger's climate classification, the climate of Glasgow (55°51'N, 04°12'W) is Cfb temperate climate, especially mild due to strong maritime influences. With significant precipitation in all seasons (average annual precipitation = 1100 mm), the average maximum temperatures in the warmest months (July and August) remain below 20°C, but with at least five months averaging above 10°C (UK Met Office).

The thermal comfort survey was conducted in 6 monitoring points in the pedestrian area of Glasgow, a stretch of approximately 1.5 km between Argyle Street and Sauchiehall Street, covering most of the Buchanan Street, in the shape of a "Z" (Fig.1). For the area surveyed, conditions of exposure varied from locations close to crossroads to monitoring points within street canyons, with the sky view factor ranging 0.38-0.45. Each point was revisited at least three times, so that a comparative number of questionnaires were obtained for each location (procedure adopted in order to minimize local, context-related influences).

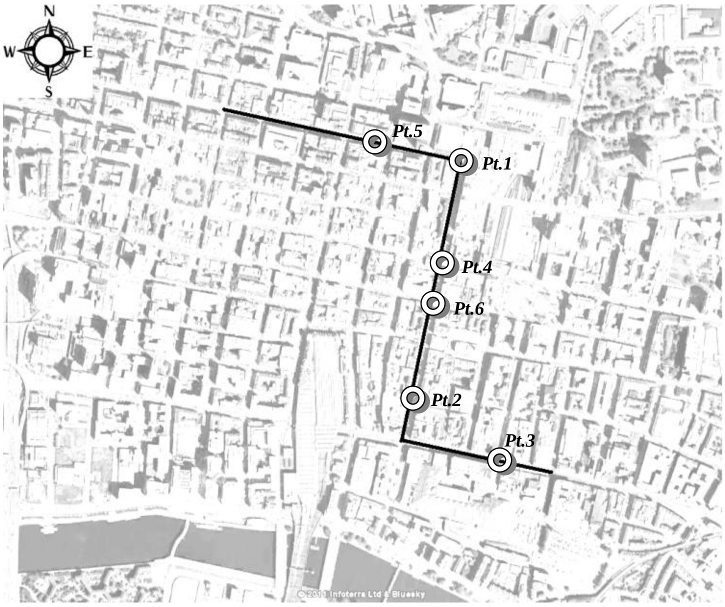



**Figure 1.** Monitoring points along the pedestrian area.

Climate measurements and field surveys were carried out between March and July 2011, over 19 outdoor survey campaigns, covering a wide range of weather types, though mostly under clear-sky conditions. Monitored climatic variables (air temperature and humidity, wind speed and direction, solar radiation and globe temperature) were according to ISO 7726 (ISO 1998) standards. Each measurement/survey campaign spanned up to three hours (typically from 10am to 1pm, local time). Climate measurements employed a Davis Vantage Pro2 weather station (Figure 2), equipped with a three cup anemometer (at approximately 1.5 m above ground), air temperature and humidity sensors at 1.1 m above ground and a silicon pyranometer at 1.4 m. Additionally, a globe thermometer was prepared for assessing the Mean Radiant Temperature ($T_{mrt}$), which consisted of a gray sphere[1] with an enclosed temperature data logger (Tinytag-TGP-4500), attached to the tripod at 1.1 m above ground, with sufficient distance to the pole so as to avoid overshadowing of the globe. Resolution and operational ranges of the equipment are shown in Table 1. Data from all sensors were registered by a logger and recorded every five seconds, and averaged over one minute. $T_{mrt}$ was calculated according to ISO 7726 for forced convection (Eq. 1) from the measured globe temperature ($T_g$), wind speed ($V_a$), air temperature ($T_a$), and globe's emissivity ($\varepsilon_g$) and diameter (D).

$$Tmrt = \left\{ (Tg + 273)^4 + \left[ \frac{\left(1.1 \times 10^8 \times Va^{0.6}\right)}{\left(\varepsilon_g \times D^{0.4}\right)} \right] \times (Tg - Ta) \right\}^{1/4} - 273 \qquad \textbf{Eq.1}$$

[1] Thorsson et al. (2007) compared different methods of obtaining the Tmrt in an outdoor urban setting. From such comparisons, it was found that a hollow acrylic sphere coated in flat grey paint (RAL 7001), with a diameter of 38 mm and a thickness of 1 mm, with a Pt100 sensor at its centre, a quite similar set-up to what we adopted, provides very similar data to those obtained by integral radiation measurements in a high latitude city (Göteborg, Sweden, 57°42'N, 11°58'E).

**Figure 2.** ‘Mobile’weather station (Davis Vantage Pro2) with gray globe thermometer.

**Table 1.** Equipment characteristics

| Sensor | Resolution | Measurement range | Accuracy |
|---|---|---|---|
| Air temperature | 0.1°C or 1°C (user-selectable) | -40° to +65°C | ±0.5°C above 20°F (-7°C) |
| Relative humidity | 1% | 1 to 100% | ±3% (0-90%). ±4% (90-100%) |
| Air velocity | 0.4 m/s | 1 to 80 m/s | ±1 m/s |
| Wind direction | 22.5° | 0 - 360° | ±3° |
| Solar radiation | 1 W/m$^2$ | 0 to 1800 W/m$^2$ | ±5% |
| Air temperature (Tinytag TGP-4500) | 0.01°C | -25°C a +85°C | ±0.45°C |

Ambient temperatures measured during the campaigns ranged between 7.9 – 21.9°C, with a corresponding relative humidity range of 28 – 77%, while the mean radiant temperature range was 9.0 – 49.1°C ; wind speed range was 0 – 3.6 m/s.

A comfort questionnaire was tailored according to the recommendations of ISO 10551(ISO 1995). The first part of the questionnaire consisted of items related to personal data: gender, age, height, weight, clothing insulation (a look-up table with typical clothing garments was used[2]), time of residency in Glasgow (to account for the acclimatisation factor) and time spent outdoors before completing the survey. The second part of the questionnaire consisted of two symmetrical 7-point two-pole scales ranging from -3=‘cold’ or ‘colder’ over 0=‘neutral’ to +3=‘hot’ or ‘hotter’, used for assessing the respondent’s thermal perception and preference. Metabolic rate was assumed to be 2.8 Met for all respondents (walking at 4 km/h on level ground). The time of residency was used as a criterion of exclusion, when less than 6 months.

[2] Table A.1, Annex A, ISO 9920 (ISO, 2007).

The sample consists of 763[3] thermal sensation/preference responses. Due to more stable conditions in summer, the largest concentration of data lies within this season. With the exception of 27 cases (non residents, pregnant women, construction workers with higher metabolic rate), a total of 736 remained.

The time spent outdoors was used as a relevant parameter for narrowing the sample further as it is a controversial issue in outdoor comfort surveys. From calculations with IMEM (*Instationary Munich Energy-Based Model*) Höppe (2002) suggests that the thermal adaptation to cold is much slower than to heat, meaning that it would take several hours, if ever, until a person is fully acclimatized (i.e. with his skin/core temperatures equivalent to ambient temperature) under cold conditions. Considering the very low probability of finding a substantial amount of individuals who were exposed to outdoor conditions for longer periods when their skin and core temperatures were higher than the ambient, particularly when using "volunteers" (passers-by), a residency of at least 15 min outdoors was adopted as a criterion for the "time spent outdoors" factor. This is the minimum space residency recommended by ANSI/ASHRAE Standard 55 (2004) for indoor thermal comfort evaluations taking into account the concept of thermal adaptation.

The reduced sample with a residency time outdoors equal and above 15 min consisted of 567 individuals, 61% male and 39% female, with an age range of 12-86 years.

**Assessment of thermal indices**

For assessing the two thermal indices, PET and PMV, two softwares were employed. The PET index, expressed in °C, and defined by Höppe (1999) as the equivalent temperature to the air temperature in which, for a typical internal situation, the thermal balance of the human does not change, considering the same core and skin temperatures as in the original situation, was calculated with the Rayman software version 2.0 (Matzarakis and Rutz, 2010). For obtaining PMV, the UC Berkeley Thermal Comfort Program WinComf batch version 1.01 (Fountain and Huizenga, 1997) was employed. The applicability of both indices as predictors of thermal sensation under the monitored climate conditions was tested by binning thermal sensation data for each degree/tenth of thermal sensation vote, respectively, in both scales (PET and PMV), according to the data grouping suggested by de Dear and Fountain (1994).

Three different sets of conditions were considered for comparisons between calculated thermal sensation and actual thermal sensation: 1) minimal information regarding microclimate, gender, clothing insulation and thermal perception, 2) microclimate data, personal data (gender, age, height and weight), clothing insulation and thermal perception, 3) microclimate data, personal data, clothing insulation, thermal perception and thermal preference. The metabolic rate of 2.8 Met was assumed constant for all respondents.

For the first condition, PET was assessed from microclimate data and personal information for a standard person according to ISO 8996 (ISO, 2004) (an average 30 year old man, weighing 70 kg and 1.75 m tall and an average 30 year old woman, 60 kg and 1.70 m were used, correspondingly). Clothing values were taken from on-site

[3] Accounting for a population of approximately 600,000 inhabitants (Glasgow), with a margin of error of 5%, confidence level 95% and response distribution of 33% (comfort, discomfort due to cold or discomfort due to heat), a minimum of 340 respondents would be required.

observations and metabolic rate was kept constant. PMV was calculated from microclimate data, observed clothing levels and the fixed metabolic rate.

For the second condition, PET was calculated from microclimate data and informed personal data with respect to age, body weight and height, taking into account the clo-value observed in each case, for a fixed metabolic rate. The calculation of the PMV was based on microclimate data, observed clothing levels and a modified metabolic rate. Such modification took into account changes in basal metabolic rate due to body mass and gender effects (as discussed by Zhang et al., 2001).

Finally, for the third condition evaluated, thermal sensation was viewed in conjunction with thermal preference. Thermal discomfort due to cold/heat was only assumed when thermal sensation and preference had opposite values, such as in ‘feeling cool’(-2) and preferring ‘warmer’(+2). For a declared neutral thermal sensation (TS = 0), thermal preference was ignored.

## Comparisons between predicted and actual thermal sensation

PET

For the first condition, Figure 3 shows binned PET data for each degree in the PET scale against mean thermal sensation votes. Correlation for the whole series was high ($R^2$ = 0.82), strengthening the importance of such index for outdoor comfort studies. Diverse authors have been using PET as a relevant index for predicting outdoor comfort/discomfort (Matzarakis et al., 1999; Svensson et al., 2003, Ali-Toudert and Mayer, 2006; Thorsson et al., 2007), which suggests a high potential for employing of PET in outdoor spaces.

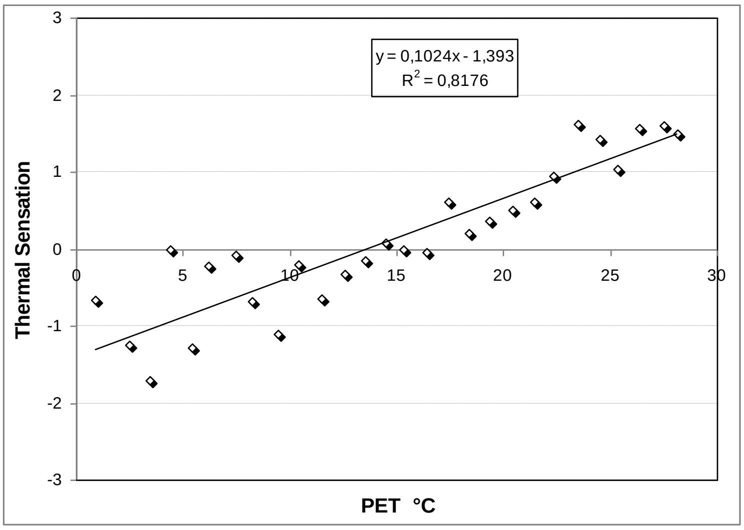



**Figure 3.** Binned actual thermal sensation versus PET.

For the second condition, besides the insertion of individual data (gender, age, weight and height) in Rayman, it was necessary to adjust the metabolic rate for each person, as the met rate is given in Rayman as Watt units. For each case, the conversion of the fixed rate of 2.8 Met was carried out by considering the Dubois area according to the expression:

$$Dubois\_area = \left(W^{0.425} \times H^{0.725}\right) \times 0.202 \qquad \textbf{Eq. 2}$$

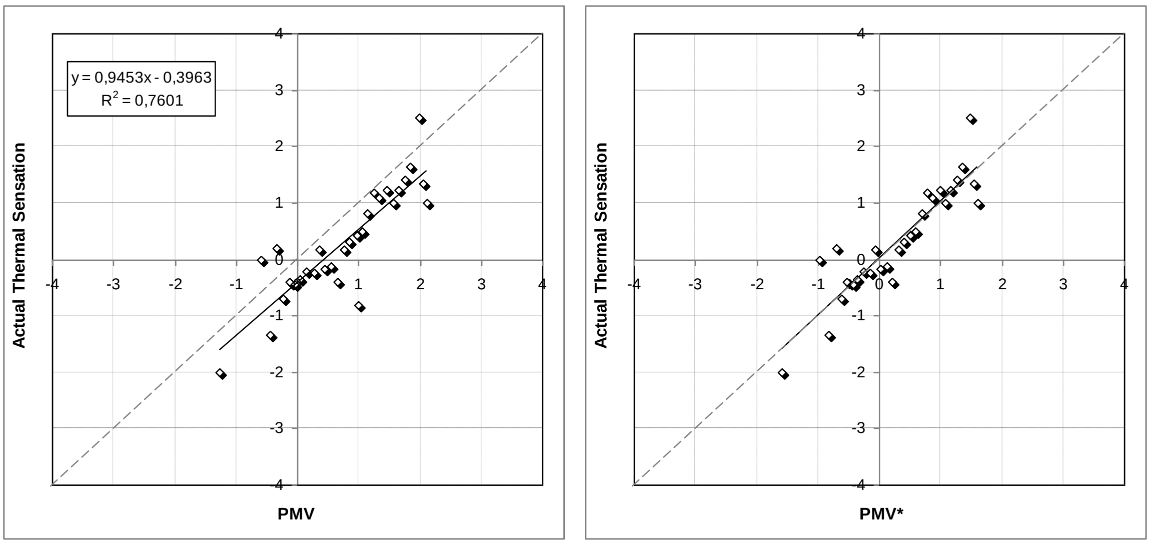
where W is weight in kg and H is height in m. The mean met rate for the sample was increased from 291 W to 301 W.

The correlation between PET results and the binned thermal sensation taking into account information gathered during the surveys with regard to personal data (age, gender, height and weight) was slightly lower than for condition 1, which used a standard person for PET calculations ($R^2 = 0.80$). Such difference however is small and not significant ($p = 0.62$). This suggests that the consideration of a standard person for PET calculations is valid and results closely resemble those from individual calculations.

For the third condition, according to the principle of assuming discomfort only in situations which showed opposite values for thermal sensation and thermal preference (TS +1, +2 or +3 and TP -1, -2 or -3), the sample was significantly reduced to 358 individuals. Correlation dropped from condition 2 to $R^2 = 0.64$. For the same reduced sample, correlation between the binned thermal sensation and PET results for condition 1 (standard person) was $R^2 = 0.63$, showing a very small relative increase when accounting for personal data. However, the difference between both is again not statistically significant ($p = 0.66$).

<u>PMV</u>

Binned data for each tenth of thermal sensation vote in the PMV scale yielded for the first condition surprisingly high correlation (Figure 4), considering that such index was developed for air-conditioned, indoor spaces. Discrepancies are found for the whole series (predicted thermal sensation is consistently lower than actual thermal sensation), pointing out to the need of applying a correction factor as shown in Figure 4b. Using the adjusted PMV*, mean bias was 0.3 thermal vote, with a maximum bias of 1 thermal vote.




a) b)

**Figure 4.** Binned actual thermal sensation versus PMV: a) without and b) with correction factor.

The modified metabolic rate was based on changes in the metabolic rate according to age, height, weight and gender. The expressions of Allen et al. (1956) and Mifflin et al. (1990) for the determination of body fat (BF) and basal metabolic rate ($Met_b$) were used to account for such effects in the total metabolic rate (basal +

muscular) which is used for PMV calculations. According to those expressions, body fat (BF in kg) is calculated differently for men (Eq. 3) and women (Eq. 4):

$$BF = 0.685 \times W - 5.86 \times H^3 + 0.42 \quad \textbf{Eq.3}$$

$$BF = 0.737 \times W - 5.15 \times H^3 + 0.37 \quad \textbf{Eq.4}$$

The fat-free body mass (FFM in kg) is obtained by subtracting BF from the body weight. Basal metabolic rate ($Met_b$ in W/m²) is then calculated the same way for male and female according to the expression:

$$Met_b = 0.0484 \times (19.7 \times FFM + 743) \quad \textbf{Eq.5}$$

The process was applied to all respondents in order to obtain the corresponding basal metabolic rate for each case. By replacing the $Met_b$ for a standard person by the modified $Met_b$ for a given individual, the total met rate used for PMV calculations was found to be slightly higher than the initial value of 2.8 Met, averaging 3.2 Met.

Correlation for binned PMV data with mean actual thermal sensation dropped significantly from the initial condition, suggesting that such a modification does not improve the thermal sensation prediction ($R^2 = 0.64$).

For the third condition, which encompasses a sample of about half of the thermal sensation votes (N=358) resulting from the combination of thermal sensation and thermal preference, correlation dropped further: $R^2 = 0.49$, by taking into account the modified metabolic rate as in the second condition, and $R^2 = 0.56$ for the constant metabolic rate (first condition). It should be stressed that the reduction in sample size may have strongly affected results. However, for the reduced sample, the obtained correlations confirm the observation made above, which suggests that a correction in metabolic rates due to gender, body mass and age does not improve thermal sensation predictions.

The space residency factor

ANSI/ASHRAE Standard 55 (2004) recommends a minimum space residency of 15 min for indoor thermal comfort evaluations taking into account the concept of thermal adaptation. ISO 10551 questionnaires are meant for a residency at least of 30 min. The data collected refer to those interviewees who were in their majority 15 min or more outdoors, decreasing gradually for longer residency periods (Figure 5).

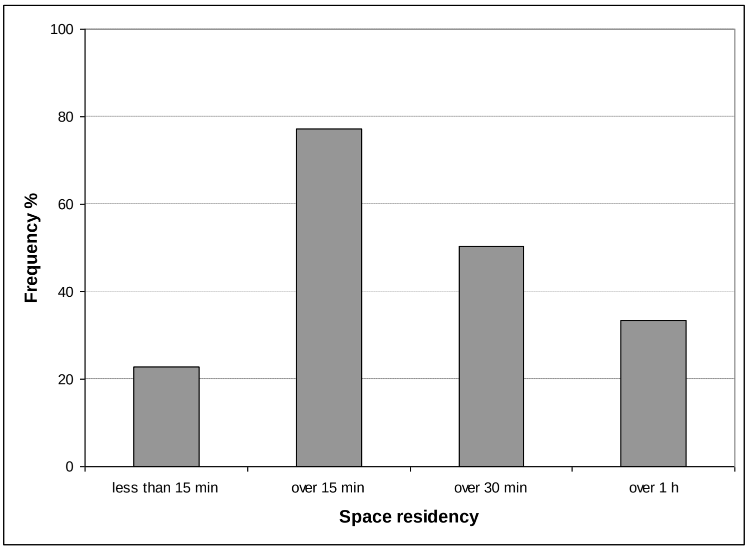



**Figure 5.** Frequency of interviewees for different period of exposure.

Since PMV and PET are both based on steady state energy-balance models, both assuming that a person has been exposed indoors (PMV) or outdoors (PET) for a long time, it was expected that respondents who declared having been exposed for longer periods would give responses more closely matching PMV/PET predictions. Although this was primarily a transversal rather than a longitudinal study where respondents could be questioned several times over given periods of exposure, this analysis can be done by looking at the goodness-of-fit of subgroups of respondents, e.g. those who declared to be outdoors: 1) less than 15 minutes; 2) from 15 minutes onwards; and 3) 30 minutes or more. For this analysis, the outdoor index PET was used. Table 2 shows comparisons between PET and mean actual sensation for 1 ºC PET bins for each subgroup and for the whole data set.

**Table 2.** Residency effect.

| **Exposure time** | **Number of respondents (N)** | **Correlation to mean thermal response ($R^2$)** |
|---|---|---|
| Less than 15 min | 167 | 0.59 |
| 15 min or more | 567 | 0.82 |
| 30 min or more | 369 | 0.73 |
| All | 734 | 0.86 |

As results obtained may be strongly related to the number of respondents in each category, it is not possible to conclude on the residency effect. The $R^2$ drop is directly correlated to a decrease in N for all cases.

## Discussion

From results obtained, simplifications in the questionnaire used for the outdoor thermal comfort surveys can be suggested. Apart from the relevant personal data regarding gender and clothing level, factors such as age, body mass and height can be fully discarded, as their effect on thermal calculations with PMV and PET is negligible. If the aim of the study is not focused on such effects (which could be analysed in more detail by means of longitudinal research), there is no need to pose such questions during the survey. Throughout the interviews, questioning age and body weight can be discomforting and on many occasions the respondent either wasn't willing to provide such information or would simply leave when asked. Furthermore, unless scales are used for measuring body weight and height, information given can be inaccurate. A large-scale validation study (Kuczmarski et al., 2001) showed that on average younger women underreported weight by approximately 1.5 kg and older persons overrated their height by 2 to 4 cm.

Data concerned with thermal preference can also be of limited usefulness as such data are difficult to interpret. The question 'Please state how you prefer to be now' is of difficult understanding. The hypothetical aspect of this question leads sometimes the respondent to think of ideal situations not directly linked to the present moment. The combined use of thermal perception and thermal preference did not show noticeable improvements when compared to using solely thermal perception votes.

With regard to the space residency effect, results obtained were not sufficient to provide any observable effect. However, such information is relevant for obvious reasons and therefore should be part of the survey. Future longitudinal studies could provide the necessary body of knowledge for establishing the minimum required space residency for outdoor comfort surveys.

It should be stressed that the indoor thermal comfort index PMV, although not appropriate for outdoors, was adopted in this study as it is based on a steady state energy-balance model (similarly to the PET index). Furthermore, as the objective of the study was primarily to check whether additional information regarding personal data would have significant effect on thermal sensation predictions, the adoption of both indices allowed us to draw conclusions which were not related to a specific thermal index (PET), but possibly also applicable to steady state energy-balance models in general. The comparatively lower correlations obtained for the PMV indicate the higher suitability of the PET index for such analyses.

Another point of discussion could be related to the use of a symmetrical 7-point two-pole scale. It could be argued that at a location such as Glasgow, outdoor climate conditions would elicit thermal sensation responses such as "very cold", what would thus suggest the need of expanding the adopted scale. However, under the conditions measured (ambient temperatures ranging 7.9-21.9°C, relative humidity 28-77%, mean radiant temperature 9.0-49.1°C and wind speed 0-3.6 m/s), the percentages of responses equivalent to -3 "cold" and to +3 "hot" were rather low (3% and 2%, respectively), with the majority of thermal sensation responses (66%) between -1 and +1. Thus, the use of the 7-point scale seems justified. Nevertheless, for more extreme conditions, the use of a 9-point scale could be more appropriate.

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