Seasonal influence on the dynamics of thermal sensation during transition from indoors to outdoors

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Abstract
We investigate acclimatization effects on outdoor thermal perception. Steady-state conditions were ensured by a prolonged stay of participants (N=16) in a test chamber prior to the subjects’ exposure to outdoors, i.e. after five consecutive hours under nearly thermal comfort conditions indoors. After that, subjects walked in a controlled pace around the external precincts of the facility and were asked to vote on their thermal sensation and preference according to a standard questionnaire: a) immediately, b) 15 minutes and c) 30 minutes after they left the controlled indoor environment. Altogether 36 sessions were performed with varying outdoor conditions over winter, spring, and summer 2015. We evaluate the effects of exposure time on the subjects’ thermal perception against predictions of the outdoor thermal conditions in terms of UTCI (Universal Thermal Climate Index) and the derived DTS (Dynamic Thermal Sensation). ANOVA results showed that UTCI conditions remained unchanged throughout the 30-min exposure time outdoors, but differed between seasons, whereas the subjects’ thermal perception votes differed both between seasons and the times of votes. Reduced thermal sensitivity was noticed in winter and spring at the first vote, resulting in greater prediction bias (underestimation), which was attenuated at higher temperatures and during longer exposure times. An initial overshooting at the first vote towards cool response occurred at moderate temperatures in summer, increasing bias (overestimation), which was also attenuated with increasing temperature and time of exposure.

Keywords: thermal sensation, transition, outdoors

1 Introduction
The paper is concerned with the “time spent in the thermal environment” question when conducting outdoor comfort studies. Short-term acclimatization plays an important role on the perceived thermal sensation, with a longer exposure of a person to the thermal environment leading to more accurate perceptions of it.

Skin temperature strongly affects how one perceives the thermal environment. Höppe (2002) shows through computer modelling of the skin temperature that in the cold at least three hours would be needed for steady state to occur in the heat exchange between skin and air temperature; in warm conditions, steady state is reached more quickly but nevertheless only after approximately half an hour.

According to the physiological concept of Alliesthesia (Cabanac, 1971) “a given stimulus will arouse either pleasure or displeasure according to the internal state of the stimulated subject”, thus stepping from thermal homogeneity to transient outdoor conditions should create immediate responses that would then diminish with time of exposure. When a subject experiences for a long time a thermally static environment, „with no opportunity for...
the body to interpret the ‘usefulness’ of a stimulus for thermoregulation”, there is a greater chance that he will more effectively experience thermal pleasure or displeasure under sudden transient conditions. De Dear (2011) pointed to the relevance of the alliesthesia concept to the planning of transitional spaces and tested this hypothesis in a climate-chamber study with participants exposed to step-up and step-down temperature changes (De Dear et al., 1993). Results described the more immediate effect in step-up than in step-down changes on reported thermal sensation; the authors suggested the accuracy in thermally perceiving a given thermal environment to be closely related to cutaneous thermoreceptors.

In this context, the “time spent...” question or the time needed for short-term acclimatization gains in importance.

As for long-term acclimatization, the adaptive comfort concept (ASHRAE, 2004) (ASHRAE Standard 55) is based on changes in thermal preference over different seasons, with increased tolerance towards heat in summer and towards cold in winter. In a field study in Israel, Pearlmutter et al. (2014) observed how expectations to seasonal changes in weather conditions affect the seasonal acclimatization factor.

In this paper we test the short and long-term acclimatization effects from subjective responses to outdoor conditions of participants who took part of a controlled field experiment over three seasons in a temperate climate (Karlsruhe, Germany).

2 Methods
The study was carried out in and outside a climate chamber located at the Karlsruhe Institute of Technology. The Laboratory for Occupant Behaviour, Satisfaction, Thermal Comfort and Environmental Research (LOBSTER) climate chamber is composed of two adjacent 24 m² offices (Figure 1). It was designed as a semi-controllable environment with operable windows where two office spaces, each provided with two workstations would closely resemble a conventional work environment. Glazings have triple-paned windows and a window-to-wall ratio of approximately 75%.

Figure 1. Floor plan and the LOBSTER test facility in summer (July 2015).

16 German males with an average height of 1.80m (SD 0.06m), weight of 80kg (SD 8.9kg), and 24.9 years old (SD 3.6) stayed for a period of 5 hours inside the chamber under
controlled thermal conditions, after which they were lead to the outdoor environment for 30 minutes. All wore sneakers, t-shirt and jeans inside the offices while outdoors they wore such ensemble underneath a standard fleece pullover and jacket (or not, depending on the season, though this was a group decision). From the clothing insulation tables (ISO 9920, 2007) the insulative value of the applied clothing was estimated to be around 0.7 clo inside and outside, in summer between 0.7 and 1.05 clo, in spring 1.3 clo and in winter 1.65 clo.

While in the office, metabolic rate corresponded to a seated position, reading and doing light work; in the open, participants were asked to walk around the climate chamber at a regular pace close to 4 km/h, so that similar conditions to the ones predicted by the human biometeorological index UTCI were met. Estimated indoor metabolic rate was 70 W/m² or 1.2 Met (ISO 7730, 1994), outdoors 135 W/m² or 2.3 Met (Bröde et al., 2012a).

Conditions monitored indoors and outdoors were the relevant thermal comfort variables air temperature, humidity and speed and the mean radiant temperature, the latter calculated according to ISO 7726 (1998). For that, two Ahlborn comfortmeters ALMEMO 2690 were used, one in each office, which were continuously monitored by the researchers who would promote slight changes in the air-conditioning system in order to ensure quasi steady-state thermal conditions within the lower and upper limits of the thermal comfort zone, given by the PMV index. During the 5-hour period in the chamber other aspects regarding indoor comfort were evaluated in a parallel study (not discussed in this paper).

Food intake and beverages were standardized for all participants, only still water and neutral, sugarless biscuits and fruits were provided during the 5-hours sessions.

After the 5-hour acclimatization period in the climate chamber, subjects were invited to leave the test facility and walk to a hand-made weather station consisting of two HOBO U12-011 dataloggers, one of which was placed within a plastic 15 mm globe painted grey for recording globe temperature; and the other logger hung on a string inside a 50 cm-long PVC tube for preventing direct solar radiation while allowing natural ventilation to the logger. Spot measurements of wind speed were taken using a hand-held anemometer (Testo 416 Mini-Vane anemometer), which had been attached to the tripod. Back-up data from the roof-top Thies weather station, located at 6m from ground level on the roof of the climate chamber were also used. Measurements on soil were close to the respondents, air temperature and humidity sensors at 1.30 m, globe thermometer at 1.2 m and anemometer at approximately 1.6 m.

A standard comfort questionnaire was given to the subjects at three different time stamps: immediately after leaving the test chamber; after 15 min of light walk around the LOBSTER facility; and after further 15 min walking outside. In this paper, we focus on reported thermal sensation according to the German version of the 7-point perceptual judgment scale with a neutral point (ISO 10551, 1995). Groups of four were tested each day and for three consecutive days per season, so that each individual would repeat two times the experimental procedure, hence a total of 9 days per subject.

Indoors, the PMV (ISO 7730, 1994) thermal comfort index was used for the thermal evaluation of the offices. Indoor thermal conditions were real-time monitored with the Ahlborn comfortmeters and post-processed in the UC Berkeley Thermal Comfort Program WinComf batch-version 1.01 (1994-1995) for assessing PMV data.
Outdoors, thermal conditions were post-processed with the non-steady state Universal Thermal Climate Index (UTCI), which is based on a multi-node model of human thermoregulation (Fiala et al., 2012) using the approach of equivalent temperature. For a direct comparison to the reported thermal sensation votes, the UTCI-Fiala model also predicts thermal sensation (Bröde et al., 2012b; Fiala et al., 2003), termed ‘Dynamic Thermal Sensation’ (DTS).

Monitored data were analysed by applying mixed-model ANOVA (Littell et al., 1996) and by means of locally estimated smoothing splines (LOESS) (Zuur et al., 2009). Results include thermal votes reported in three different time stamps over three days within three seasons (Table 1). In total, 48 sessions are evaluated in this paper, encompassing a total of 417 thermal votes.

### Table 1. Breakdown of experimental sessions.

<table>
<thead>
<tr>
<th>Season</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>winter</td>
<td>January 12 through February 6</td>
</tr>
<tr>
<td>spring</td>
<td>April 13 through May 8</td>
</tr>
<tr>
<td>summer</td>
<td>June 22 through July 17</td>
</tr>
</tbody>
</table>

### Results

Outdoor conditions measured over the three seasons are varied, including mild days in winter, unexpected warm days in spring and heatwave episodes in summer. ANOVA results (Table 2) showed that the climatic conditions as assessed by UTCI (Figure 2) remained stable during the 30 min exposure time, but differed between seasons.

![Figure 2. UTCI, thermal sensation & preference related to season and exposure time. Individual data and smoothing function (LOESS) with 95% CI for time effect.](image-url)
Table 2. ANOVA results with numerator (NumDF) and denominator degrees of freedom (DenDF), F- and P-values for UTCI, thermal sensation (TS) and thermal preference (TP) depending on season and exposure time.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Num DF</th>
<th>Den DF</th>
<th>F Value</th>
<th>P-Value</th>
<th>F Value</th>
<th>P-Value</th>
<th>F Value</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Season</td>
<td>2</td>
<td>33</td>
<td>56.19</td>
<td>&lt;.0001</td>
<td>65.92</td>
<td>&lt;.0001</td>
<td>61.37</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Exposure Time</td>
<td>2</td>
<td>33</td>
<td>1.85</td>
<td>0.1739</td>
<td>7.47</td>
<td>0.0023</td>
<td>3.26</td>
<td>0.0524</td>
</tr>
<tr>
<td>Exposure Time*Season</td>
<td>4</td>
<td>33</td>
<td>3.49</td>
<td>0.0175</td>
<td>2.53</td>
<td>0.0497</td>
<td>4.29</td>
<td>0.0042</td>
</tr>
</tbody>
</table>

Furthermore thermal sensation and preference both differed between seasons and exposure times (Figure 2, Table 2). The statistically significant interaction effects (Exposure Time*season) indicate that time courses were modified by season, with e.g. a slight increase of thermal sensation votes with time in spring and summer compared to a slight decrease in winter.

The sensitivity of thermal sensation on UTCI related to season and exposure time is analysed by LOESS in Figure 3. The curves’ shape depended on season and exposure time and the non-monotonous LOESS curves shown in Figure 3 for winter and spring just after transition (at time stamp 1 or at 0 min) resembled the linear shape found in summer at later times. There was also a pronounced initial overshooting response in summer with cooler reported thermal sensation at identical UTCI (~20°C) compared to spring and winter.

Figure 3. Sensitivity of thermal sensation on UTCI related to season and exposure time analysed by LOESS smoothing functions with 95% CI.

Figure 4 shows the mean prediction error (bias) of DTS (Dynamic Thermal Sensation) for the three UTCI ranges, as a function of season and exposure times. The reduced thermal sensitivity in winter and spring at 0 min (cf. Fig. 3) result in greater bias (underestimation), which were attenuated at higher temperatures and during longer exposure times. In addition, the initial overshooting cool responses in summer increased bias (overestimation), which was also attenuated with temperature and time of exposure (Table 3).
Table 3 illustrates the time course of bias and root-mean-squared prediction error (rmse) for the different seasons showing that bias and rmse were reduced after 15 min in winter and after 30 min in summer, respectively, whereas for spring there was not much change in rmse and even a slightly increased bias.

Table 3. Mean prediction error (bias) and root-mean-squared error (rmse) of DTS (Dynamic Thermal Sensation) related to season and exposure time.

<table>
<thead>
<tr>
<th>Season</th>
<th>bias</th>
<th>0 min</th>
<th>15 min</th>
<th>30 min</th>
<th>rmse</th>
<th>0 min</th>
<th>15 min</th>
<th>30 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>-0.12</td>
<td>0.00</td>
<td>-0.02</td>
<td></td>
<td>1.10</td>
<td>0.71</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>Spring</td>
<td>-0.19</td>
<td>-0.43</td>
<td>-0.52</td>
<td></td>
<td>1.03</td>
<td>0.94</td>
<td>1.12</td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>0.45</td>
<td>0.31</td>
<td>0.03</td>
<td></td>
<td>1.03</td>
<td>1.07</td>
<td>0.94</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.04</td>
<td>-0.05</td>
<td>-0.18</td>
<td></td>
<td>1.05</td>
<td>0.92</td>
<td>0.99</td>
<td></td>
</tr>
</tbody>
</table>

4 Discussion and Conclusion
In this study, we compare TSV against predicted thermal sensation (DTS) with the non-steady state index UTCI. Results suggest that the longer exposure time will reduce prediction errors and therefore lead to more consistent thermal votes’ estimates. A longer exposure proved to be advantageous in the three seasons evaluated, which could be regarded as a necessary condition for validating thermal votes in outdoor comfort surveys.

From previous research on transient indoor conditions (De Dear et al., 1993) which have indicated that, when moving from indoors to outdoors during winter time, the initial thermal sensation responses could be biased against cooler TSV, our results support the recommendation to consider only thermal responses for respondents with longer occupancy in the outdoor environment. In view of the strong need to standardize procedures in outdoor comfort surveying (Johansson et al., 2014), the main contribution of
the study is to set a minimum of 30 minutes as the suggested permanency in the outdoor environment in the case of field studies.

The consideration (for evaluation purposes) of thermal votes reported in a shorter timeframe from the last indoor exposure –whatever thermal history the subject might have experienced prior to the questionnaire survey, could lead to significant errors in calibrating existing comfort indices or in proposing comfort ranges for a given population.

Acknowledgements
We acknowledge the Brazilian research funding agency CAPES, the European Union 7th Framework Programme (FP7/2007-2013) grant agreement no. PIRG08-GA-2010-277061 and the Fachgebiet Bauphysik & Technischer Ausbau/Karlsruher Institut für Technologie (fbta/KIT), in special Marcel Schweiker and Andreas Wagner.

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