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Analyzing thermal comfort perception of students through the class hour, during heating season, in a university classroom

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A B S T R A C T
Indoor to outdoor transitions, and the subsequent occupant adaptation, impact thermal perception of occupants and their evaluation of a building. A mixed methods thermal comfort study in a classroom of Eindhoven University of Technology was conducted to provide a better understanding of thermal perception of students as they move into and adapt to their classroom environment. Data was collected over two weeks during heating period, with different heating set-points. A total of 384 students, in seven undergraduate level lectures, participated voluntarily. The thermal sensation vote, obtained at different time points through classes — 10 min, 20 min, and 45 min — was found to be significantly different (p < 0.05). In the start of a lecture, perception varies primarily depending on the outside temperature, operative temperature, gender, and where the occupant came from. Comparing the two weeks’ observations, second week having a 1.5 °C lower set-point, revealed that the most considerable differences occurred in the immediate response phase after indoor–outdoor transition. For nearly 20 min post transition, participants retain a thermal memory of their last exposure, gradually adapting as the lecture proceeds.

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1. Introduction

Educational buildings need to stimulate student productivity and learning. Studies show a reliable association between classroom thermal environment and air quality with student performance and well-being [1]. Simultaneously, as the need for low-energy buildings grows, classrooms must also follow suit. Standards, such as ISO 7730, EN15251 and ASHRAE Standard 55, provide guidelines on indoor comfort in classrooms. Yet, several studies note high levels of dissatisfaction among students regarding thermal comfort and air quality in classrooms and student thermal preference not being accurately reflected by the provisions in relevant standards [2–6]. This is even true for classrooms in developed countries [7]. In contrast to office workers — who are often the primary target of thermal comfort standards — students are frequently moving between different rooms, or even buildings, and have different clothing patterns. Thus, at least part of the comfort mismatch may be ascribed to standards neglecting students’ transitional thermal comfort needs. What may exacerbate classroom thermal discomfort issues are the high occupant density and restrictions on occupant behaviour. Such restrictions make clothing adjustments the single most favoured means of adaptation for students [2].

To save energy and to improve the thermal comfort in a university classroom, standards could prescribe more dynamic/flexible ranges, supporting heterogeneity and individual based needs [8,9]. However, for such dynamic standards to be successful, a better understanding of thermal comfort in classroom and student perception and expectations is needed.

Thermal comfort research has primarily focussed on occupants in steady conditions, including the two most popular comfort models in current use: the PMV and adaptive thermal comfort models. There have been relatively fewer studies dealing with thermal comfort during spatial transitions. Some such studies have looked into clothing adjustment effect [10], consumption of food and/or beverages [10–12], and changes to activity level [13]. Change of thermal sensation vote, during spatial transition across environments with different thermal conditions, has been noted to relate to the temperature difference between the two spaces [14]. Most studies agree that the change in thermal perception subsequent to spatial transitions cannot be accurately gauged using the
abrupt jumps being more likely to be perceived than changes in magnitude [16]. However, when subject to temperatures that are perceived by the occupants as uncomfortably cold or warm, transitions of even 1 °C are noticed [16].

Field investigations — with actual occupants in real buildings — are rare. This work tries to address the gap using a transverse thermal comfort study in a classroom of the Eindhoven University of Technology. We aim at improving provisions for classroom thermal comfort by gaining a better understanding of responses to spatial transitions in thermal environment and the corresponding breadth of occupant flexibility. This should be helpful in achieving optimal energy usage for thermal comfort. It was also envisaged that this study can act as a pilot, with an exploratory conception, to help the design of future similar studies in the field, involving actual occupants.

2. Methods

The studied classroom (Classroom 8, 15 × 14 × 7 m, CL8) is in the Auditorium of the Eindhoven University of Technology, the Netherlands. Surveys were undertaken during four lectures in the second week (7–11) and three lectures in the fourth week (21–25) of March, 2016. A modified field study protocol was designed, based on existing literature [18,19], to evaluate thermal perception as the class progressed. It consisted of the following steps: collecting information on the building and the conditioning system, environmental measurements alongside subjective surveys, and correlating objective and subjective data.

2.1. Building characteristics

Being in the Auditorium’s basement, CL8 is windowless and is minimally affected by outdoor elements. It can seat 200 students. Typically, lectures are during the five weekdays and each lecture is scheduled as 2 × 45 min, with a 15 min break in between. The conditioning system in the Auditorium operates in three temperature ranges, depending on occupancy, time of day, and day of the week, as depicted in Fig. 1.

The system does not have seasonal variations and occupancy detection operates in an on/off fashion, independent of the actual number of students. The Building Management System (BMS), which controls the conditioning, relies on a temperature sensor in each classroom. No avenues for occupant control are present. As per requirement, preheated/pre-cooled outdoor air, is supplied under the seats for ventilation. Ventilation air outlets are located in the ceiling. During heating season, the radiator placed under the blackboards is operated since the teacher’s position does not have ventilation air inlets. After detection of an empty room, an offset of 30 min is allowed before switching back occupancy state to unoccupied.

2.2. Objective measurements and subjective surveys

Prior to the surveys, a set of preliminary, measurements were carried out in the classroom. These confirmed that the ventilation, luminosity, draught, and background noise levels in the room were in accordance with the revised guidelines set for new and renovated classrooms in the Netherlands, targeting “Fresh Schools” [20]. Hence, these parameters were not continually measured during the surveys. During classes surveyed, measurements were done for air and globe temperature, relative humidity, air speed, and CO2 levels. These sensors were put together to create an indoor comfort measurement stand (ICMS), which was located centrally in the room. There were four more temperature sensors spread across the classroom. The set-up for these sensors is shown on a lay-out of the classroom in Fig. 2. The devices were located at about the head/face level for sitting students and they recorded data once every minute. This is also the frequency of the BMS temperature sensor. Specifications of the instruments are given in Table 1. Operative temperature (Top) was calculated using globe temperature and air temperature (Tair) measurements. Air velocity within occupied zone always kept below 0.2 m/s, most of the time being <0.15 m/s.

Outdoor temperature data was provided by a BMS measurement location on the Auditorium’s roof. These values were used to calculate a seven day prevailing mean outdoor air temperature (PMOAT), based on the arithmetic mean of the daily average outdoor temperature [21].

The subjective survey questionnaires consisted of two parts: a general survey and a set of three right-now surveys. Contents for each part have been enlisted in (Fig. 3 a). Images of the full questionnaires have been provided as Supplementary documents (Supplementary Fig. 1 for general survey questionnaire and Fig. 2 for right-now questionnaire). Optical mark recognition was used to scan the filled up paper responses into a database [22]. Survey time-line is presented in (Fig. 3 b).

The general survey questionnaire was filled at the beginning of lectures. The three right-now surveys were intended to identify students’ thermal perception evolution through the class duration. Review of works done in climate chambers and studies on visitors in a museum suggested that people take about 20 min to adjust to an altered thermal environment [9,23]. It is also understood that following a change from higher activity rates to sedentary state, occupants require ~15 – 20 minutes to be able to respond to their current thermal environment [6,24]. Hence, the time points for...
right-now surveys were chosen as 10 min (Period A, within transition), 20 min (Period B, at edge of transition), and 45 min (Period C, lecture’s end). To minimize the impact of the survey during the lecture, the right-now surveys were kept brief. Both thermal sensation (TSV) and thermal preference (TPV) were queried on the ASHRAE seven point scale, taking cue from an earlier work [25]. The thermal comfort (TCV) was queried on a six point scale, from ‘Very uncomfortable’ to ‘Very comfortable’ (numerical equivalents 1–6).
The general survey questionnaire queried the participants' mode of travel. The options given were those typically used by students, which have quite varied metabolic rates [26]: walking (2.9–5.3 met); riding a bicycle (4.7–7.8 met); riding a motorised two-wheeler (2.5 met); riding/driving a car (1.4 met); riding in bus/train (1.4 met). When the departure location was answered as from within the building, travel method is taken as walking. Sometimes the travel mode question had multiple responses. In this case, depending on the departure location, a logical choice was made for the travel mode. For example, for departure from a building on campus, the mode can only be walking or riding bicycle.

Ensemble clo values were calculated by summing individual clo values [21]. For jackets, gloves, and scarves, clo values were taken from other sources [27–29]. Additional values for undergarments (0.04 clo) and socks (0.04 clo, when occupants reported that they were wearing shoes) were added to the ensemble values. Since the chairs in CLB are wooden, chair insulation was not considered.

During Survey Week 1 (SW1), BMS default set-points continued. However, it was observed, both during preliminary measurements and during SW1, that the temperature in the classroom kept consistently higher than the set-point by ~2 °C. Temperature measured by the BMS sensor did not agree with Sensor 4, which had been calibrated before commencing measurements. To address this issue, as well as to analyse the influence of indoor temperature on student perception immediately following the outdoor–indoor transition, the set-points were lowered by 1.5 °C during Survey Week 2 (SW2). Occupants (students and teachers) were kept unaware of this change.

The survey was transverse in nature. Based on time-table data, to examine the effect of outdoor–indoor transition on student thermal perception, we focused on such classes which were the “first lecture” of the day for the respective students. The respective faculty members were contacted for their approval of a survey during their lecture hour. Following these communications, seven different courses were finalized. During weeks prior to the surveys, the students in these classes were briefed regarding the survey that they would be expected to participate in. It was explained that it was part of an ongoing study for a student project and their participation was to be entirely voluntary and if they did decide to participate it would be taken as their consent. They were also intimated that they may provide their feedback in a free and open-minded manner since the data collected would be treated confidentially and would solely be used for the purpose of this study. They were also briefed as to the language and terminology of the questionnaire and when, during the class, they were expected to fill up the questionnaire.

2.3. Data analysis

Missing answers or unrealistic values (e.g., no top half or bottom half clothing selected, for clo values) were disregarded. Such instances were less than 5% of the total number of responses. IBM SPSS Statistics 23 was used for statistical analysis. Choice of specific statistical tests depended on the distribution of the collected data.

Since most of the parameters surveyed presented non-normal distributions, two-sided Wilcoxon rank test was used for determining significant differences. For pairs with significant difference, follow-up one-sided tests were conducted. To test for significant differences in TSV for period A (TSVA) across travel methods and departure locations, Kruskal-Wallis test was used. All tests used α value of 0.05. Correlations were evaluated using Pearson product moment correlation.

Temperature variations during lectures and at different points in the room are presented in Fig. 4. Across CLB, temperature differences were significant for both weeks (p < 0.001, differences ≤ 2 °C). Air temperature increased as one gets further from the instructor’s podium. During SW1, the highest temperatures were noted for Zone 2 (Fig. 2), possibly because students mostly concentrated around zone 2 during all the lectures. Specific seating pattern varied with each lecture. To give due consideration to seating location, for every lecture, a weighted average temperature was calculated across the seating zones using Eqn. (1).

$$ T_{air\, weighted} (°C) = \frac{\sum_{i=1}^{4} N_i T_{air\,i}}{\sum_{i=1}^{4} N_i} $$  \tag{1}

In Eqn. (1), Ni represents number of students in zone ‘i’ and Tair,i is the air temperature of zone ‘i’. Air temperature from the ICMS was used for Zone 2. Temperature of different zones during Period A was calculated as average over the first 15 min of the lecture hour. Similarly, the temperatures for period B and C were calculated respectively over 10–25 min and 35–45 min.

3. Results

A total of 7 lectures were surveyed: two morning and two afternoon lectures in SW1 (206 students); three afternoon lectures in SW2 (178 students). Of the respondents, 56% were male and 73% were aged between 18 and 20 years. Most of the respondents (318 out of 384) entered the classroom from outside the Auditorium. During SW2, the outdoors were significantly (p = 0.013) warmer than SW1.

The seating location of the students failed to show any significant correlation with their TSVs for all three periods. This was true for both when seating location was taken on the 12 point grid (Supplementary Fig. 1) — p-value 0.42 to 0.19 — or for the four zones corresponding to each air temperature sensor — p-value 0.55 to 0.10. Hence the weighted mean temperature was deemed a feasible alternative.

3.1. General survey questionnaire

In the general survey, on the seven point Likert scale querying ability of the classroom to act as a good learning environment, majority of the students (76%) opined on the “agreeable” side. Further, in the question asked in the right-now surveys regarding any complaints they may have with indoor environmental quality, 62% of the responses had no issues. The complaints were mostly about noise (14%), followed by lighting (10%). Temperature measurements and participant subjective responses for both weeks, have been summarized in Table 2 for ease of reference.

3.2. Classroom conditions

3.2.1. Carbon dioxide levels and humidity

For most lectures, the CO2 levels started at ~ 600 ppm and rose to a stable value within 15 min. No correlation was found between the CO2 levels and number of students. But CO2 levels did not cross 900 ppm for any of the lectures, staying below 750 ppm most of the time.

Absolute humidity levels remained nearly consistent through classes, variation being ≤ 0.5 gm/kg of dry air (< 1% variation in terms of relative humidity). Actual values kept between 3.5 and 6 gm/kg of dry air, well below the 12 gm/kg of dry air upper limit [21]. Fifty percent of all responses preferred the humidity conditions as they were.

3.2.2. Indoor temperature

Operative temperature was calculated using the weighted air
temperature (from Eqn. (1)) and the globe temperature from the ICMS. During the lectures, Top increase keeps within 1 °C, except for the first lecture in SW1 when the rise was closer to 1.5 °C. The increase is at least partly due to the occupancy. However, across the three Periods, Top differences were not significant (Wilcoxon Signed Ranks Tests; Top,A vs. Top,B: p = 0.08; Top,B vs. Top,C: p = 0.23; Top,A vs. Top,C: p = 0.18). As may be noted from Fig. 5, the operative temperature almost consistently keeps beyond the zone intended by the BMS (grey shaded region in the plot), even though the set-points had been lowered for SW2. There also existed considerable temperature differences across the classroom’s span, as already discussed in Section 2.3.

3.3. Factors influencing thermal perception during Period A

A major objective was to identify factors that affect TSV immediately after the transition. Queries regarding these factors were contained in the general survey: mode of travel, point of departure, prior food/beverage consumption, and use of any medical aids (distribution of votes summarized in Table 3).

Occupant TSV\textsubscript{A} had a significant correlation with the outdoor temperature (r = 0.25, p < 0.001) and the difference between outdoor and indoor temperature from Period A (r = 0.26, p < 0.001). These correlations, though statistically significant, are quite week. During Period A, occupant TSV did not significantly correlate to clo value (p = 0.78). Also, as discussed further in Section 3.4.5, TSV for Period A did not differ significantly between the groups who did and did not adjust their clothing — ‘Adjust’ and ‘No adjust’ groups respectively.

3.3.1. Consumption of food and beverages

Food/beverage intake is likely to have an effect on occupant thermal sensation. Gender wise, no significant difference (p = 0.31) in food/beverage intake was noted. For TSV\textsubscript{A}, across the different combinations of food and beverage consumption, there was no significant difference. Kruskal-Wallis test was carried out for different data groupings, including all responses, responses that involved only a single choice of food/beverage (‘Single answers’ in

<table>
<thead>
<tr>
<th>Table 2 Summary of measured and surveyed parameters.</th>
</tr>
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<tbody>
<tr>
<td><strong>SW1</strong></td>
</tr>
<tr>
<td>Tair</td>
</tr>
<tr>
<td>Period A</td>
</tr>
<tr>
<td>Period B</td>
</tr>
<tr>
<td>Period C</td>
</tr>
<tr>
<td>Top</td>
</tr>
<tr>
<td>Period A</td>
</tr>
<tr>
<td>Period B</td>
</tr>
<tr>
<td>Period C</td>
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<tr>
<td>TSV</td>
</tr>
<tr>
<td>Period A</td>
</tr>
<tr>
<td>Period B</td>
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<td>Period C</td>
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</tr>
<tr>
<td>Female</td>
</tr>
<tr>
<td>Overall</td>
</tr>
</tbody>
</table>

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*Fig. 4. Temperature variation in CL8 over the survey weeks, for different lectures. Air temperature for zones 1, 3, and 4 come from sensors 1, 2, and 3 [Fig. 2] while for 2 it is taken from the ICMS.*
3.3. Medical aids

The question formulation asking for use of medical aids by the students was found to have been confusing for the participants. Zero responses were for ‘None’ while the majority were for ‘Other’. Hence, it was decided to interpret all answers for ‘Other’ as ‘None’, i.e., no medical aids used. Effect of use of medical aids was analysed by examining student thermal sensation, thermal comfort (TCV), and humidity sensation votes (HSV). Kruskal-Wallis test was carried out for ‘All responses’ taken together while Wilcoxon rank test was used for the simplified groupings. Results have been provided in Table 5.

3.3.3. Mode of arrival at the classroom

In addition mode of travel, students had also been queried if they were coming from within the same building, a different building on campus, or a building off-campus/home. The difference in TSVa for the three departure locations was examined using Kruskal-Wallis test. These values were significantly different (p < 0.001). Pairwise comparison of TSVa for the different starting points is given herewith:

- Home/off-campus vs on-campus: p = 0.024
- Home/off-campus vs within Auditorium: p < 0.001
- On-campus vs within Auditorium: p = 0.003

The travel methods were examined separately for each departure location. The Kruskal-Wallis test is used to test for significant difference in TSVa between the different travel methods per departure location. No significant differences were found in the TSVa values for departure location on-campus (p = 0.19) or off-campus (p = 0.53).

When walking indoors (students who came from within the building) is excluded as a mode of travel, no significant difference was found across the clo values of students arriving by different modes (p = 0.72). When including students coming from within the building, a significant difference for clo values was noted (p = 0.001). Interestingly though, students coming from within the Auditorium had a higher mean clo value (0.93) than those coming from outdoors (0.75).

3.3.4. Tracking the thermal perception differences through Periods B and C

During Periods B and C, differences of travel method, clo adjustment, and departure location did not create significant difference in TSVa values. In Period B, medical aids did not significantly differentiate TSV, TCV, and HSV values. For both Periods B and C, significant differences existed between TSV of students who had a cold beverage and students who had a warm one prior to class, the
ones having had a warm beverage feeling warmer ($p = 0.012, 0.022$ respectively). For the responses from Period C, use of medical aids did not significantly differentiate the TSV or HSV of students. But in Period C, students not using medical aids were more comfortable than who were (from TCV values, $p = 0.005$).

3.4. Student thermal perception development through the class

3.4.1. Thermal sensation votes

Student thermal sensation, taken together for both weeks (Fig. 6), significantly differed across the three periods, even though the operative temperature did not.

- TSV$_A$ vs. TSV$_B$: $p = 0.001$
- TSV$_B$ vs. TSV$_C$: $p = 0.002$
- TSV$_A$ vs. TSV$_C$: $p < 0.001$

Indoor air temperature for the two weeks were significantly different, SW1 being on average warmer by ~ 1.5 °C. Following this, the TSV values for Period A and B differed significantly between SW1 and SW2 ($p < 0.001$ and $p = 0.03$ respectively), as illustrated in Fig. 7. However, this was not the case for TSV$_C$ ($p = 0.32$).

Only during Period A, did TSV have a significant correlation with the operative temperature ($r = 0.34, p < 0.001$). The plots for TSV vs operative temperature for all three periods have been shown in Fig. 8. It may be observed that the correlation for Period A, though significant, is still quite weak. For Periods B and C, correlations were even weaker ($r = 0.19$ and $0.18$, respectively) and neither of the correlations were significant at 5% level.

Also, only during Period A are the TSV values from the two genders significantly different ($p = 0.03$), women feeling cooler.

3.4.2. Thermal comfort votes

Any TCV of just comfortable or better is regarded as comfortable. No correlation was detected between TCV and TSV. Table 6 provides the percentage of votes rated as comfortable.

From Table 6, for most instances, comfort rating was close to 80%. SW1 had a slightly better comfort rating based on TCV. Also, TCV, unlike TSV, did not differ significantly across the Periods.

3.4.3. Thermal preference votes

Thermal preference votes did not differ significantly across the Periods (Wilcoxon Signed Ranks Tests; TPV$_A$ vs. TPV$_B$: $p = 0.93$; TPV$_B$ vs. TPV$_C$: $p = 0.81$; TPV$_A$ vs. TPV$_C$: $p = 0.80$). Since the ASHRAE 7-point thermal sensations scale was used both for TSV and TPV, under ideal comfort circumstance, TPV should be equal to TSV. Similarly, TPV < TSV signals a desire to be cooler and TPV > TSV signals a desire to be warmer. These three groups (cooler, no change, and warmer) are summarized in Table 7.

3.4.4. Occupant clothing

The average clo value during the survey was 0.78 clo. The clo values for the two genders did not differ significantly ($p = 0.35$). Gender differences were also absent for clothing adjustments ($p = 0.29$). A moderate correlation exists between MOAT and clo values ($r = 0.28; p < 0.001$). Clo values for SW1 and SW2 were significantly different ($p = 0.002$).

3.4.5. Clothing adjustment

Clothing adjustment is the primary adaptive opportunity available to students inside classrooms. To determine the influence of clothing adjustment on thermal sensation, students are divided in two groups based on responses to the right-now survey. The first group did not adjust their clothing in the period immediately preceding the survey time point while the second group did (Table 8). Very few responses (total 4) marked that garments were added and hence these were excluded. Thus, all Adjust responses considered, correspond to clothing reduction.

Clo values, as ascertained from the general survey at the beginning of the lecture, of the two groups (‘Adjust’ and ‘No adjust’) for Period A were significantly different ($p = 0.015$), the ‘Adjust’ group having lesser clothing insulation (mean clo of 0.75 vs 0.83). Irrespective of the Period considered, the TSV values for Adjust and No adjust group did not differ significantly (Period A, $p = 0.53$; Period B, $p = 0.36$; Period C, $p = 0.09$). Most of the students adjusted their clothing only once (153) or not at all (132). Clothing adjustments two or more times were reported by 99 participants.

4. Discussions

The prime challenge of this study was gauging occupant thermal comfort perception across a transition for real occupants. The results suggest that the survey was effective, with minimal number of unusable entries, and provided reliable results. To conduct such surveys successfully, an important guideline is to ‘keep it short’. A clear explanation of the questionnaire language and purpose prior to starting the survey, as was done in this case, was possibly also helpful in obtaining unambiguous responses and improving the willingness of students to participate. Thus, such explanations and participant interaction is advisable for similar studies in future.

The form of questionnaire (paper-based, web-based, or phone app-based) is also becoming an important decision. Since in our situation, the students were coming into a classroom, mostly intent on taking notes, paper based questionnaire was deemed as the ideal solution. Once inside the classroom, students settled down to a relatively constant activity. In situations/transitions where this is not so, a question regarding current activity would need to be added. Question and options formulation (wording) remains important aspect. As we noted, clothing adjustment did not significantly influence students’ thermal perception. This seems counter-intuitive. It could be that the question posed was not appropriately interpreted by the students. In future studies, it would be useful to explicitly link clothing adjustments with indoor thermal conditions and reformulate the question in the following manner:

“Did you adjust your clothing in the (enter preceding time period) mins of the lecture?”

- Yes
- No
If answered Yes to previous question, were the adjustments due to the temperature in the classroom?

- Yes, I took off clothing because it was warm
- Yes, I added clothing because it was cold
- No, adjustments not due to temperature

Being an exploratory/pilot study, the number of participants was limited to the classes studied over the two weeks. Though 384 participants gave their feedback, due to the number of factors being considered in Section 3.3, the levels of significance obtained from the tests may yet be questioned. For the influence of different factors examined in Section 3.3, responses from both weeks were considered.

Table 6
Percentage of TCV “Just Comfortable” or better.

<table>
<thead>
<tr>
<th>Period</th>
<th>SW1 (%)</th>
<th>SW2 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>80</td>
<td>72</td>
</tr>
<tr>
<td>B</td>
<td>83</td>
<td>82</td>
</tr>
<tr>
<td>C</td>
<td>80</td>
<td>73</td>
</tr>
</tbody>
</table>

Fig. 7. Illustration of evolving TSV across the three periods, separated by SW1 and SW2.

Fig. 8. Plots of TSV vs operative temperature (with small artificial jitter added to distinguish points) for all three periods (a) Period A (b) Period B (c) Period C. The regression line for Period A has also been plotted.

“…”

because of outdoor influence since it is located in the basement. The BMS sensor location, which meant the system kept going even with required set-point having been reached, could also have compounded the issue.

In Fig. 5, wide diversity of thermal conditions across the lectures is noteworthy. And the lectures with warmer temperatures did not necessarily have greater number of students. This could be due to the differences in outdoor conditions. A further plausible reason is also the HVAC system itself. As described earlier, it does not distinguish how many occupants are present, just if the room is occupied or not. The room has a capacity of 200. Hence, the system is particularly unable to maintain a consistent operative temperature through a class with low occupancy (for example, Lectures 1 and 4 in Fig. 5). This observation suggests the need for a system that has a occupancy control proportionate to number of students present and not just in an on/off fashion.

Comparing the results for SW1 and SW2, it is apparent that the adaptation phase is prevalent for nearly the first twenty minutes post-entry. Such a time duration has also been noted with visitors in a museum [23].

Across the Periods, the significant difference between TSV points towards students gradually adapting to the classroom thermal environment. Past period B though, adaptation is nearly complete and difference between TSV_B and TSV_C was not large. By period B and C, there is a marked shift of votes from ±1 on thermal sensation scale, towards neutral. One factor that could have resulted in bias in the responses from the students is the repeated administration of the questionnaire over the class duration. Prior to beginning the surveys, the explanation provided to participants did not mention anything regarding gradual adaptation or variation of thermal perception with time. However, it is plausible that the repetition of right-now questionnaires could have influenced the students to gradually change their vote. On the other hand, no significant difference was noted for the TCV values across the periods. This leads us to believe that the role of participant bias may not have been much in the observed results regarding TSV variation.

During Period A, TSV differs between the two genders but this difference ceases to exist as time progresses. The TSV difference cannot be explained in terms of inter-gender clothing differences. The difference is possibly an artefact of the outdoor-indoor transition and since women are likely more sensitive to transitions [9]. The results imply that the two genders started at different thermal positions and since women are likely more sensitive to transitions [9]. The difference is possibly an artefact of the outdoor-indoor transition and since women are likely more sensitive to transitions [9]. The results imply that the two genders started at different thermal positions and since women are likely more sensitive to transitions [9].

During Period A, the explanation provided to participants did not mention anything regarding gradual adaptation or variation of thermal perception with time. However, it is plausible that the repetition of right-now questionnaires could have influenced the students to gradually change their vote. On the other hand, no significant difference was noted for the TCV values across the periods. This leads us to believe that the role of participant bias may not have been much in the observed results regarding TSV variation.

Even though \( T_{\text{int}} \) was warmer during SW1, no stark differences are noted for the percentage of TSV = TPV, between the two weeks (Table 7). In SW2, the distribution across the three possible thermal preferences is more even and more consistent across Periods. SW1 distributions are quite similar to SW2 for Period B and C. In Period A, for SW1, a majority wanted to feel cooler. Students gradually adapted to the circumstances of the classroom so that by Period C, the spread across desire for warmer and cooler had evened out. But the TPV_A for SW1 is a clear indication that CL8 is warmer than it needs to be, possibly for the reasons discussed in Section 2.2. Since for both weeks, students seem to adapt themselves to the prevalent conditions and towards end of class, thermal preferences are nearly uniformly divided, it makes sense from the energy viewpoint to operate at the lowered set-point.

That the warmer conditions of SW1 did not result in different perception after students had time to adjust to the indoors — noted from both the TSV and the TPV — is indicative of a significant level of adaptation among them. Similar results were obtained from the study in a university classroom in Florida when students, after having sat through an hour of class, could not distinguish between
temperature conditions different by 2 °C or if the temperature had been increasing/decreasing during the class [31]. In a stark contrast though, among passengers waiting in a railway station the desire for comfort — as deduced from the neutral temperatures — increased as the waiting period increased [32]. This could be because for passengers, the average indoor temperature was beyond comfort boundaries while in the classroom studies, the indoor conditions were still within ASHRAE comfort zones. The fact that the passengers were waiting for their train connection might also have played a role.

During Period A, Top was a key factor. As noted in Section 3.4.1, this is the only Period when TSV correlates with Top. After the transition, students take some time to adapt to the changed Top. But in Period B and C, as adaptation progresses, the correlation between Top and TSV ceases to exist.

Contrary to expectations, the correlation between clo and PMOA estimated a rise in clo insulation with warming conditions. This points to the risk of forming conclusions regarding relation between clo value and weather, based on data over a brief period. Another reason for the counter-intuitive result could be the unreliability of clo values gathered through occupant feedback. This must be another important consideration in questionnaire formulation.

Period A witnessed the most fraction of clothing adjustment. The fractions were similar for Periods B and C. This is to be expected since most students had just come into the classroom in Period A. In terms of clothing adjustment, the ‘Adjust’ group having lower clothing insulation than the ‘No adjust’ group may be ascribed to long-term adaptation. Somebody who feels warm in general, would tend to wear less clothes out of experience, and vice versa. But since TSV did not significantly differ between these groups, it is implied that people adjusting their clothing did so to be able to positively affect their thermal sensation and achieved their intention. The individual preference and corresponding adjustments may also help explain the lack of correlation between clo and Top.

Students were asked about their clothing ensembles only upon having entered the classroom. They could have taken off jackets at the coat racks near the entrance to the building, thus leading to the lack of difference in clo values for respondents using different travel modes. However, students inside the auditorium already have adapted to the building and accordingly modified their clothing. It turned out that this was a greater insulation value than for people just entering the building, as seen in Section 3.3.3.

The results showed that food/beverage consumption in the immediate preceding time period, the mode of travel, and use of medical aids were not major factors of influence on TSV. This is not to deny that food/beverage consumption does not impact body metabolism or thermophysiological responses. The implication is that their effect on subjective thermal sensation is negligible post a major jump across thermal environments. In fact, the effect of food/beverage consumption on TSV did crop up for Periods B and C.

4.1. Implications for practice

As noted from the current studies, during the heating season, with transition occurring from cold outdoors to heated indoors, post-transition, there is an initial leeway of nearly 20 min. It took this duration for the bulk of adaptation of the students to be complete. Thus, HVAC system set-points during the beginning of the day may have relaxed requirements. As long as they gradually warm up to values within the winter comfort zone (20–24 °C) over the first 20 min of the class, student comfort needs would be satisfied. In fact, the gradual warming, instead of an already warm room, may even aid the initial adaptation of the students. Given the exploratory nature of this study though, it would be needed to validate the findings across seasonal variations and in buildings with other usage profile as well.

5. Conclusion

Thermal perception, during transition, may be impacted by nonthermal factors as well. The transition thermal perception can have an impact on how occupants evaluate the indoors, especially in situations of temporary occupancy like classroom, auditorium, museums, cinema halls etc. This work attempted at identifying the factors that had a significant influence on TSV in the phase immediately subsequent to a spatial transition and understand the gradual adaptation to the new thermal environment. Clothing, clothing adjustment, food/beverage consumption, travel method, and use of medical aids did not have a distinguishing effect on the TSV in the phase following the transition. What had a consistent impact was the environments across which the transition occurred.

Despite thermal conditions during the classes not changing much, student thermal perceptions changed significantly as the class progressed. This gradual adaptation lead to gender distinctions of TSV ceasing to exist. The correlation between operative temperature and TSV also receded and thermal preference evened out. Especially interesting was that these phenomena occurred for both weeks even when indoors were warmer during SW1 by an average of 1.5 °C. The gradual adaptation raises implications for energy efficient operation of HVAC systems. To improve thermal comfort, such a system would need to work in sync with evolution of thermal perception, with relaxed set-points at the start of each period. This would require the system to be more flexible and dynamic. Further knowledge regarding such transitions would need to be obtained across seasons and building types to aid and guide the design of better HVAC systems and BMS control profiles.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.buildenv.2017.09.016.

References