Occupant response to transitions across indoor thermal environments in two different workspaces


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ABSTRACT

Keywords:
Thermal comfort
Indoor transition
Office space
Hospitals
Field study

To understand how transition across different thermal zones in a building impacts the thermal perception of occupants, the current work examines occupant feedback in two work environments—nursing staff in hospital wards and the workers in an office. Both studies used a mix of subjective surveys and objective measurements. A total of 96 responses were collected from the hospital wards while 142 were collected from the office. The thermal environment in the hospital wards was perceived as slightly warm on the ASHRAE thermal sensation scale (mean TSV = 1.2), while the office workers rated their environment on the cool side (mean TSV = −0.15). The results also show that when the transitions were across temperature differences within ±2 °C, the thermal perception was not impacted by the magnitude of the temperature difference—acting in occupant thermal sensation and thermal comfort/thermal acceptability vote. This would imply that the effect of temperature steps on thermal perception, if any, within these boundaries, was extremely short lived. These findings go towards establishing the feasibility of heterogeneous indoor thermal environments and thermal zoning of workspaces for human comfort.

1. Introduction

Research efforts and standards regarding indoor comfort have been primarily focused on occupants in a steady frame and do not stress on spatial thermal transitions [1,2]. Relatively fewer works have looked at occupant perception during transitions, looking at adaptation time and thermal perception immediately following transitions across different thermal environments [3].

Studies have looked at the effect of transitions across large temperature differences, which would be emulative of an occupant moving between outdoors and indoors, in controlled, laboratory conditions [4–10] and field settings [5,11–15]. A distinction has been noted between laboratory and field studies, the proposition being that under field conditions, occupants quickly passing through transitional spaces can adapt their thermal expectations over a wider range [5]. Some recent works have also examined and analysed thermal perception of occupants moving into and out of temporarily occupied spaces like malls, markets, and railway/bus stations and airports [16–21].

Results from these studies implied that thermal exposure history [5,8,15], duration spent in a transitional space [18,21], and magnitude of the air temperature difference across which the transition was made [11] impacted thermal perception during transition. They also point to the fact that for comfortable occupants, changes of ≤2 °C magnitude go unnoticed [11,14] but occupants who are uncomfortably cold or warm would notice even transitions of 1 °C [11].

The aforementioned works focused on how the spatial transition between outdoors and indoors affects occupant perception. However, the spatial transitions that occupants have to regularly go within a building have not been studied under field settings, with only one work coming close, in a controlled, laboratory setting [6]. As the modern office space rapidly evolves, with concepts like flexible working space, and layouts imposing break rooms along with work spaces, design of office HVAC systems would need to be considerate of such spatial transitions. Thermal zoning of indoor space, depending on orientation, usage, and occupancy, varying set-point air temperature across the floor space can be utilised to improve comfort while also saving energy [3,6,22]. This is also of relevance with the shift towards renewable energy [23]. This shift makes energy supply variable and intermittent and synchronization of demand and supply would likely introduce variabilities in the indoor thermal environment [24].
Laboratory experiments have proposed an acceptable magnitude of 3 °C for thermal steps in terms of thermal perception [3,9] and of 4 °C in terms of thermoregulatory burden [25]. In this work, the thermal comfort perception of occupants was examined as they moved across different thermal environments within their everyday workspaces. One case examined thermal perception of nursing staff in hospital wards. The other did the same in a university office building, involving academic staff in cellular offices, by targeting their movement between office space and the adjoining hallways and pantry space, which they used only during short transitions, as different from their regular workspace. The university office building was chosen as a representative for typical, cellular office spaces.

In a hospital, different occupant groups have different thermal preferences [26]. There are, to mention a few groups, patients, visitors, and the caregivers. Since they have different clothing and activity levels, their thermal preferences also vary. Considering that there is a dearth of literature regarding thermal comfort of care-professionals, a pilot, mixed methods study had been undertaken to examine the thermal comfort perception of nurses. A complete description of the study and the results regarding thermal comfort perception of nurses and how it affects their self-assessed work performance have been reported in a recent work [27]. Fortuitously, nursing staff also have to frequently move across rooms/zones with different functional purposes. The active nature of the nurses’ job also contrasts well with the near sedentary nature of the office workers’ activities, providing a chance to examine how spatial transitions affect thermal perception over a wider occupant activity range.

Since the works performed in climate chambers suggest that thermal perception is not significantly affected when the air temperature difference across which the transition takes place keeps within ±3 °C, we intended to verify if a similar conclusion may be reached for similar magnitudes of temperature transitions in workspaces. It was intended to ascertain this through occupant feedback regarding thermal sensation and acceptability/comfort.

2. Methods

Measurements in the hospital wards were carried out during 11–29 July (First period) and 7 October–11 November (Second period), 2016. The wards had patient rooms and the nurses’ break room positioned along their perimeter while the reception, medicine room, meeting room, and chief’s office are positioned in the core of the building, >8 m from the façades. The offices examined were in a building of the Eindhoven University of Technology. Unlike the hospital wards though, the office occupants can open their room’s window and adjust the Building Management System (BMS) temperature settings over a range of ±3 °C (depending on the prevalent conditions and the demand on the induction unit). The occupants cannot see the actual set temperature value. Measurements in the office were conducted during 31 October–4 November (First period) and 21–25 November (Second period), 2016. In both settings, it was preferred to divide the measurements over two periods so as to provide the participants an intermediate break period. The break lowered chances of onset of survey fatigue and also let us do some preliminary analysis of the participant responses, ensuring they were not being inconvenienced by either the subjective or the objective portion of the surveys.

The office building was located within the University’s campus and surrounded by other similar buildings that housed both classrooms and administrative facilities. It is at least 300 m from any major roads and the campus itself has over 35% of its area under greenery coverage. The hospital is about 3 km from the city’s centre and the ward itself is about 300 m from the nearest major road. While there are other buildings on the north and south of the hospital, on the east and west, the hospital is bordered by green space, which are parks and gardens. Both locations have similar climate, a temperate oceanic climate as per Köppen classification. The average maximum and minimum annual temperature for both locations are close to 14.5 and 6 °C, respectively.

Both workspaces have spaces with different thermal conditions, across which the occupants have to move in course of their regular work related activities. This provided an opportunity to study occupant perception immediately following such spatial transitions. We focused only on transitions that were between different portions of the workspaces and not transitions between outdoor-indoor or between different buildings.

2.1. Preliminary measurements

Before starting the surveys, preliminary measurements of indoor thermal conditions were conducted. This was done in order to better understand the buildings' thermal environments, helping decide on the sensor locations during the actual survey periods.

An interview with the head nurse provided an overview of the most frequent transitions nurses made in their workday (presented in Fig. 1). Preliminary measurements were performed at locations based on this information, using two stands that had three Rotronic sensors (specifications in Table 2), each measuring temperature and humidity. In these measurements, the reception, medicine room, nurses’ break-room, the corridors, and some patient rooms with different bed numbers and different orientations were covered. Air temperature and relative humidity (RH) stratification over 0.1, 1.1, and 1.7 m never exceeded the device accuracies in any of the locations. Therefore, stratification concerns were absent. BMS sensors were not available through out the hospital wards. Hence, we placed our own sensors across the locations of interest.

Preliminary measurements were also carried out in the office building which showed that the difference in measured values between the calibrated sensors and the BMS sensors and air temperature stratification, measured over 0.1, 1.1, and 1.7 m, were within instrument specifications. Therefore, during the surveys, a single temperature sensor was placed close to the participants, at their desk height, and in the hallways, at a height of 1.1 m.

2.2. Subjective survey

2.2.1. Participants

Demography of the nursing staff, who responded to the survey, has
Table 1
Demographics of nurses responding to the surveys.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Number of responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age groups</td>
<td></td>
</tr>
<tr>
<td>&lt;20</td>
<td>1</td>
</tr>
<tr>
<td>21–30</td>
<td>75</td>
</tr>
<tr>
<td>31–40</td>
<td>12</td>
</tr>
<tr>
<td>41–50</td>
<td>15</td>
</tr>
<tr>
<td>51–60</td>
<td>6</td>
</tr>
<tr>
<td>&gt; 60</td>
<td>1</td>
</tr>
<tr>
<td>Gender</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>20</td>
</tr>
<tr>
<td>Female</td>
<td>90</td>
</tr>
</tbody>
</table>

Table 2
Specifications of the equipments used for indoor measurements.

<table>
<thead>
<tr>
<th>Device</th>
<th>Model</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hospital</td>
<td>ICMS (For hospital wards) — 3 in numbers</td>
<td></td>
</tr>
<tr>
<td>RH/CO2 Sensor, E + E Elektron</td>
<td>EE30 series</td>
<td>RH [10–90%, ±3%] &amp; CO2 [0–2000 ppm, ± 50 ppm]</td>
</tr>
<tr>
<td>Omnidirectional anemometer</td>
<td>HT-412</td>
<td>var [0.05–1 m/s, ±0.02 m/s±1%]</td>
</tr>
<tr>
<td>Sensor/Anemo transducer</td>
<td>Black sphere with Globe temperature</td>
<td>[−5–40 °C, ±0.1 °C]</td>
</tr>
<tr>
<td>Temperature sensor</td>
<td>NTC thermistor U-Type</td>
<td>Air temperature [−5–40 °C, ±0.1 °C]</td>
</tr>
<tr>
<td>Temperature and humidity sensors — 9 in numbers</td>
<td>Rotronic</td>
<td>Air temperature [0–50 °C, ±0.3 °C] Humidity [10–90%, ±3%]</td>
</tr>
<tr>
<td>Offices</td>
<td>Temperature sensors</td>
<td>Eltek</td>
</tr>
<tr>
<td>BMS sensors</td>
<td>Honeywell</td>
<td>T7500A100</td>
</tr>
</tbody>
</table>

been summarized in Table 1. Upon entering the hospital building, nurses first go to the dressing room — located in the basement — to change into their work uniform and then come to the wards. So, by the time they come up to the ward, they have had spent over half an hour post their outdoor-indoor transition. Since, from previous studies, we estimate that the outdoor–indoor transition impacts on occupant thermal perception for ~20 min [13,15], it was assumed that the outdoor–indoor transition did not impact any of their responses. Nurses are required to wear the same work clothing over the entire year, to which, they may add on an extra vest. They may choose to wear additional clothing as long as it does not make up the outermost layer. This is due to hospital policy on hygiene and patient safety. Typical work schedule for the nurses, along with the transitions they make across thermal zones, have been presented in Fig. 1.

In the office building, six persons, working in different cellular offices on the fifth floor of a seven storied building, agreed to participate. There were three male and three female participants, aged between 30 and 60. For both cases, no restrictions were imposed upon normal behaviour of the participants and measurements were carried out so as to be minimally invasive of their work space, in consultation with them.

Before starting the surveys, the participants from both groups were briefed about the terms used in the surveys and how and when they were expected to fill up the survey sheets. They were requested to fill in the survey immediately following a spatial transition, preferably within 20 min. They were asked to fill up surveys as many times as they were comfortable with, throughout their workday. If something unusual happened during the transition, they were asked to mention it as a comment in the survey. Participants were intimidated that their participation would be entirely voluntary and they could discontinue at any time if they wanted. In the hospital, an overall approval was also obtained through the chief nurse while the office participants signed an informed consent.

2.2.2. Subjective thermal perception

Subjective thermal comfort sensation data was collected using sets of questions. For both groups, the questions were presented in Dutch since they were all native Dutch speakers. The complete survey questions have been given in Supplementary documents, translated to English for readers’ convenience (Supplementary Fig. 1 for hospital and Supplementary Fig. 2 for the office question sets). Their content has been briefly summarized in Fig. 2. Due to the small and specific number of participants in the offices, age was only queried once, at the beginning of the survey.

In the office, occupants had been advised to fill up the questionnaire once they had come back to their desk after a brief excursion to the common spaces (copy room, coffee room, pantry etc.) in and around the hallway. These were all connected and hence had similar thermal conditions. The nurses had been asked to fill up the questions as per their convenience, as often as they could, following any spatial transition they had undergone within the building. So, they were queried both their current and past location over the past 30 min. Questions for both groups were of the ‘right-now’ type, that is, asking for the participant’s perception of the thermal environment they were experiencing right at that moment.

For providing the survey sheets in the hospital, the nurses’ breakroom was chosen. There, they could pick up blank sheets and drop-off filled ones. In the office, survey sheets were provided to the occupants on their respective work desks and were collected back from their offices. During the survey weeks, it was checked regularly to confirm that survey sheets had not been exhausted and they were intermittently restocked.

The right-now surveys queried occupant thermal sensation vote (TSV) on the ASHRAE seven-point thermal sensation scale: Cold (−3), Cool (−2), Slightly cool (−1), Neutral (0), Slightly warm (1), Warm (2), Hot (3). Occupant comfort level was queried on a six point scale: Very comfortable/Very acceptable (1), Comfortable/Acceptable (2), Just comfortable/Just acceptable (3), Just uncomfortable/Slightly unacceptable (4), Uncomfortable/Unacceptable (5), Very uncomfortable/Very unacceptable (6). The questionnaire for offices used the six point scale for describing thermal comfort (TCSV) while for the hospital, the questionnaire queried thermal acceptability (TAV). This
2.3. Objective measurements

Outdoor temperature data for both locations were taken from the appropriate KNMI (Royal Netherlands Meteorological Institute) webpages [29]. Prior to the surveys, all equipments to be used had been calibrated.

In the hospital wards, measurements of air temperature and RH were carried out at several locations, based upon the determinations made during the preliminary measurements and on typical transitions nurses made within the ward. These locations have been specified in Fig. 3. Temperature and RH sensors (Rotronic) were placed across patient rooms with different orientations. Apart from them, three indoor climate measurement stands (ICMS) were also employed. Sensors mounted on these stands measured air temperature, globe temperature, omni-directional air velocity, air humidity, and CO2 concentration at a height of 1.1 m, i.e., at about the height of centre of gravity for standing occupants [2]. Two ICMS were placed in two patient rooms, having different orientations, while one was kept near the reception. Data from the different sensors was logged using a Grant Squirrel 2040 datalogger.

In the offices, temperature sensors (Eltek GC-05/GD-05) (Temperature inside desk sensor) were positioned within 1 m of each participant, at about their desk height, while avoiding being too close to heat/radiation sources, like the computer, screen, or window. The sensors were either positioned on the participants’ working desk or, when available, on a supplementary desk they used primarily for keeping documents, books etc. We refer to these as the desk-sensors, as opposed to the BMS sensors which were near the room’s door and not in the occupant’s immediate vicinity. This set-up has been represented as a sketch in Fig. 4. For the office space, since we had a fixed and small number of participants, the sensor locations could be decided in consultation with them so that the sensors were located within a meter of their seating location while keeping away from their devices and the windows. Additionally, in both workspaces — hospital and office — the air temperature sensors were located within radiation shields so as to minimise the confounding effect of radiant temperature. In the hallway, there was another temperature sensor, of the same make, mounted on a pole at the height of 1.1 m. Temperature readings were recorded by Eltek GENII Rx250 A L Logger. The BMS sensor was a Honeywell T7560A100 Digital Wall Module ((Tair,BMS)).

2.4. Data analysis

For the nursing staff, responses that had missed out on marking their current and/or previous location could not be linked to a specific air temperature and hence had to be excluded. If they marked that they had been in three or more locations over the past 30 min, such responses were excluded as well. Similarly, the office personnel did submit some responses after they had come in from outside the building — at the beginning of the day or post lunch or a meeting. Such responses were deemed unusable and only responses involving transitions within the building were used.

For the data obtained from the hospital wards, since the before and after location of the surveys could vary a lot, a MATLAB script was used to connect the filled in locations with the corresponding temperature measurement devices, using the time-stamp of recorded data. Measurement data was averaged over 10 min and the data of the 10-min value closest to the survey time stamp was used. Since the transition was easier to track in the office space — participants always filled up the form after coming back to their desk from the hallway space — matching a survey moment with the appropriate recorded air temperature was simpler and could be done with spreadsheets.

For both cases, SPSS was used for statistical analysis. The t-test was used to detect significant differences for normally distributed data while Wilcoxon rank test was used for non-normal distributions. Since most of the parameters surveyed presented non-normal distributions, two-sided Wilcoxon rank test was used for determining significant differences. When a significant difference was obtained, follow-up one-sided tests were conducted. Pearson product moment correlation was used to examine correlations between parameters. Linear regression analysis was used to develop equations correlating thermal sensation and thermal comfort/acceptability and thermal sensation and air temperature. Neutral temperatures were derived from equations correlating thermal sensation to temperature, by setting thermal sensation to neutral (0 for the current case). Since, for studies involving humans, r values of even ±0.3 would indicate moderate correlation [30], Table 7.3, p. 113], we include correlations with r close to 0.3. All statistical tests have been reported along with their p-values to provide readers with an idea about the significance of the tests.

Temperature steps for transitions were calculated as given in Eqns. (1)-(3).
\( \Delta_{T_{air}} = T_{air, current} - T_{air, previous} \)  \hspace{1cm} (1)

\( \Delta T_{air, desk - sensor} = T_{air, desk - sensor} - T_{air, hallway} \)  \hspace{1cm} (2)

\( \Delta T_{air, BMS} = T_{air, BMS} - T_{air, hallway} \)  \hspace{1cm} (3)

As discussed in Section 2.3, each temperature sensor had a margin of error of \( \pm 0.3 \) °C. Hence, calculated temperature differences had an error margin of \( \sqrt{0.3^2 + 0.3^2} = 0.4 \) °C. The cases where the temperature differences were within this margin of error were considered to be without a thermal step. Transitions occurring across air temperature differences larger than these levels, that is transitions with a thermal step, were compared with the transitions without thermal steps. The transitions were also divided into warm and cool transition groups, depending on if the previous air temperature was lower (warm transitions) or higher (cool transition) than current air temperature. This was done keeping in mind that differences between thermal perception following warm and cool steps have been noted in previous works \[22,31]\.

TSV depends on the experienced thermal environment. When the thermal environment differed significantly across the instances being compared, the comfort temperature \( T_c \) calculated using Griffiths' equation \[32\] (Eqn. (4)) was also used for comparisons, to provide a more unbiased perspective, since it depends both on TSV and the thermal environment. In Eqn. (4), the slope ‘m’ was taken as 0.5 \[32\].

\[ T_c = T_{air} - \frac{TSV}{m} \]  \hspace{1cm} (4)

3. Results

Occupant responses and indoor and outdoor air temperatures during the surveys have been summarized in Table 3. The survey in the hospital wards yielded 132 responses (89 from first period and 43 from second). Office surveys yielded 186 responses (110 from first period and 76 from second). A total of 96 usable responses were gathered from the nursing staff, 59 responses during the first period and 37 during the second. From the office personnel, 142 usable responses were gathered, 84 during the first period and 58 during the second. The six participants in the office, each provided between 19 and 25 responses.

From the data gathered in the office space, the following was noted:

- \( T_{air, desk - sensor} \) and \( T_{air, BMS} \) did not significantly differ between the two periods (\( p = 0.17 \) and 0.089, respectively)
- TSV did not significantly differ between the two periods (\( p = 0.54 \))
- First period's hallway air temperature was significantly warmer (\( p < 0.001 \)) — 20.4–23.2 °C (mean = 22.2) vs 21.3–22.6 °C (mean = 21.9)
- \( \Delta T_{air, desk - sensor} \) (Eqn. (2)) and the \( \Delta T_{air, BMS} \) (Eqn. (3)) did not differ significantly between the two periods (\( p = 0.68 \) and 0.13, respectively)

Table 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Max</th>
<th>Min</th>
<th>Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hospital wards</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TSV</td>
<td>3</td>
<td>−3</td>
<td>1.2 (1.4)</td>
</tr>
<tr>
<td>TAV</td>
<td>6</td>
<td>2</td>
<td>3.8 (1.3)</td>
</tr>
<tr>
<td>Indoor air temperature (°C)</td>
<td>26.6</td>
<td>20.9</td>
<td>23.3 (1.0)</td>
</tr>
<tr>
<td>Outdoor air temperature (°C)</td>
<td>32.2</td>
<td>0.5</td>
<td>15.7 (5.0)</td>
</tr>
<tr>
<td><strong>Offices</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TSV</td>
<td>1</td>
<td>−2</td>
<td>−0.15 (0.63)</td>
</tr>
<tr>
<td>TCV</td>
<td>2</td>
<td>5</td>
<td>2.4 (0.66)</td>
</tr>
<tr>
<td>Desktop air temperature (°C)</td>
<td>25.5</td>
<td>19.3</td>
<td>22.5 (1.0)</td>
</tr>
<tr>
<td>BMS air temperature (°C)</td>
<td>24.0</td>
<td>19.5</td>
<td>21.8 (0.84)</td>
</tr>
<tr>
<td>Outdoor air temperature (°C)</td>
<td>16</td>
<td>1</td>
<td>7.9 (2.0)</td>
</tr>
</tbody>
</table>

Similarly, data from the hospital wards, across the two periods may be contrasted thus:

- \( T_{air, current} \) and \( T_{air, previous} \) were warmer during the first period (\( p < 0.001 \) for both)
- TSV was significantly warmer for the first period (\( p < 0.001 \))
- \( \Delta T_{TSV} \) did not differ significantly across the two periods (\( p = 0.87 \))
- Nurses’ \( T_c \) did not differ significantly between the two periods (\( p = 0.051 \))

The two periods of measurements had outdoor conditions changing over a reasonably broad range. However, based on the aforementioned findings regarding the indoors and temperature steps during transitions, responses from both periods were analysed together for each workspace, while results from each workspace were interpreted independently.

3.1. Occupant perception

3.1.1. Hospital wards

For the hospital wards, air temperature in the current and previous location of each survey response have been visualized in Fig. 5 using boxplots. As may be noted, the values were similar for current and previous location. This may be since all locations in the wards could be, for different responses, both the current and the previous location. However, this does not represent the temperature differences experienced during individual transitions, which have been depicted later in Fig. 7. No significant difference was found when comparing the self-reported current and previous activities of the nursing staff (\( p = 0.60 \)).

For all responses together, TSV was significantly correlated with current air temperature (\( R^2 = 0.22, p < 0.001 \)) and the resulting neutral temperature was 21.7 °C. Additionally, TSV also had a moderate correlation with \( T_{air, previous} \) (\( r = 0.37, p < 0.001 \), neutral temperature = 21.1 °C).

Similarly, TAV also correlated significantly (\( p < 0.001 \)) with \( T_{air, previous} \) (\( r = 0.41 \)) and \( T_{air, current} \) (\( r = 0.45 \)). A strong, significant correlation was found between TSV and TAV — Eqn. (5). The optimal TAV, minima of regression line, lies just on the cooler side of the TSV scale (TAV = −0.47), indicating that the nursing staff find a “slightly cool” work environment most acceptable.

\[ TAV = 0.29 - TSV^2 + 0.27 - TSV + 2.49; R^2 = 0.73, p < 0.001 \]  \hspace{1cm} (5)

3.1.2. Offices

For the offices, to calculate \( \Delta T_{TSV} \), the previous air temperature was always taken as the air temperature in the hallway while current air temperature was taken as the air temperature within the office. The air temperature in the hallway and office space (both desk-sensor and BMS sensor), for each survey response, have been visualized in Fig. 6 using boxplots. The \( T_{air, desk - sensor} \) was significantly warmer than \( T_{air, BMS} \) (\( p <
For all responses together, TSV significantly correlated with current air temperature, recorded by both desk-sensor ($R^2 = 0.11$, $p < 0.001$) and BMS sensor ($R^2 = 0.23$, $p < 0.001$). Desk-sensor data yielded a neutral temperature of 23.2 °C while BMS data led to a neutral temperature of 22.1 °C. This follows logically from the fact that $T_{\text{air, desk-sensor}}$ was consistently higher than $T_{\text{air, BMS}}$ for the same instances of measurements.

As in the hospital wards, here too TSV had a moderate correlation with the air temperature from the previous location, i.e., $T_{\text{air, hallway}}$ ($r = 0.43$, $p < 0.001$, neutral temperature = 22.3 °C). This is similar in magnitude to the value obtained when correlating TSV with BMS data. TSV had the strongest correlation with $T_{\text{air, BMS}}$ ($r = 0.49$).

A significant correlation was found between TSV and TCV (Eq. (6)). The optimal TCV, minima of regression line, lies on the warmer side of the TSV scale ($T_{\text{SV}} = 0.56$). TCV correlated to $T_{\text{air, BMS}}$ ($r = 0.27$, $p < 0.001$) and $T_{\text{air, hallway}}$ ($r = 0.34$, $p < 0.001$) but not with $T_{\text{air, desk-sensor}}$ ($p = 0.09$).

$$\text{TCV} = 2.78 \cdot \text{TSV}^2 - 3.10 \cdot \text{TSV} + 2.37; \quad R^2 = 0.28, \quad p < 0.001$$

### 3.2. Spatial transitions

#### 3.2.1. Hospital wards

The transitions without a significant thermal step (i.e., within the margin of error of 0.4 °C) numbered 57 while those with a recorded thermal step-change were 39. The boundary of this error margin is indicated using a grey shading in Fig. 7. The figure provides scatter plots of TSV (Fig. 7 a)) and TAV (Fig. 7 b)) values with $\Delta T_{\text{air}}$. The TAV value of transitions without thermal steps were significantly higher ($p = 0.001$), implying a better thermal perception in presence of thermal steps.

For both transition groups (with and without a thermal step) correlations with their respective current air temperature were significant (respectively $r = 0.52$, $p < 0.001$ and $r = 0.43$, $p < 0.001$), leading to neutral temperatures of 21.3 °C and 22.1 °C, respectively, for the group without a thermal step and the group with a thermal step. But, the $T_c$ (Eqn. (4)) calculated for the two types of transitions did not differ significantly ($p = 0.07$), indicating that thermal sensation of the nurses kept pace with the air temperature they faced.

Unlike $T_{\text{air,previous}}$ and $T_{\text{air, current}}$ though, $\Delta T_{\text{air}}$ for all the transitions taken together did not correlate with TSV ($p = 0.37$) or TAV ($p = 0.92$). This lack of correlation may also be seen from a visual inspection of Fig. 7.

#### 3.2.2. Offices

Responses from the office participants were also divided into transitions with and without a thermal step. Using BMS readings, there were 65 observations in the first group (no thermal step) and 77 in the second (with thermal step-change). Using data from desk-sensors, there were 39 observations without a step and 103 with. The scatter plots of TSV (Fig. 8 a)) and TCV (Fig. 8 b)) values with $\Delta T_{\text{air, desk-sensor}}$ have been provided, with device accuracy limits (±0.4 °C) being indicated by grey shaded zones.

Maybe could add in caption: "DTair,desk-sensor±0 K is warm transition".

Similarly, scatter plots of TSV (Fig. 9 a)) and TCV (Fig. 9 b)) values with $\Delta T_{\text{air, BMS}}$ are provided, with device accuracy limits being indicated by the grey shading.

Differentiated using data from desk-sensor, the TCV values did not significantly differ between the groups with and without a thermal step-change ($p = 0.11$). However, when using BMS data to determine step changes, the group not experiencing a step had a significantly better TCV than the group with one ($p = 0.018$).

Using BMS data, the group undergoing thermal steps had a neutral temperature of 21.8 °C ($R^2 = 0.30$, $p < 0.001$), while the other group had a neutral temperature of 21.9 °C ($R^2 = 0.21$, $p = 0.001$). Using data from desk-sensors, the group undergoing thermal steps had a neutral temperature of 23.1 °C ($R^2 = 0.10$, $p = 0.001$), but for the other group, a statistically significant correlation was not found ($p = 0.14$).

Using $T_{\text{air, desk-sensor}}$, the $T_c$ values did not differ significantly between cases with and without a thermal step ($p = 0.96$). But using the $T_{\text{air, BMS}}$, $T_c$ values were significantly lesser ($p < 0.001$, 21.8 vs 22.4 °C) when thermal steps were involved, indicating that thermal steps led to warmer perception.

Similar to the transitions made in the wards, there was no...
significant correlation between TSV and \( \Delta T_{\text{air, desk sensor}} \) (\( p = 0.085 \)). TCV did not correlate with either \( \Delta T_{\text{air, BMS}} \) (\( p = 0.23 \)) or \( \Delta T_{\text{air, desk sensor}} \) (\( p = 0.90 \)). However, the \( \Delta T_{\text{air, BMS}} \) bore a significant correlation with TSV: \( r = 0.31; p < 0.001 \).

3.3. Warm and cool transitions

3.3.1. Hospital wards

In the hospital wards, the resulting TSV (\( p = 0.77 \)) and TAV (\( p = 0.96 \)) from warm (n = 32) and cool (n = 44) transitions were not significantly different. The different correlations and resulting neutral temperatures, for both warm and cool transitions, have been summarized in Table 4.

Neither TSV nor TAV correlated to \( T_{\text{air}} \) for either of warm or cool transitions. The neutral temperature, correlating TSV with \( T_{\text{air, current}} \), was higher for cool transitions by about 1 °C. However, \( T_c \) values for these two groups were not significantly different (\( p = 0.45 \)). This would again imply that the thermal perceptions were similar for both warm and cool steps.

The TAV also better correlated with \( T_{\text{air, current}} \) during cool transitions compared to warm ones (\( r = 0.51 \) vs \( 0.35 \)). This is similar to the correlations for TSV, though the difference is much larger, and suggests thermal perceptions during cool transitions relating better to the immediately experienced air temperature than those during warm transitions.

3.3.2. Offices

Differentiating based on the BMS sensor reading, the TSV values for warm transitions (n = 48) were significantly warmer (\( p = 0.01 \)) than cool transitions (n = 81) while TCV values were not significantly different (\( p = 0.46 \)). Based on desk-sensor readings, the TSV (\( p = 0.29 \)) and TCV (\( p = 0.82 \)) values were not significantly different between warm (n = 95) and cool (n = 44) transitions. The correlations, p-values, and resulting neutral temperatures, have been summarized in Table 5. From Table 5, it is quickly apparent that \( \Delta T_{\text{air}} \) did not correlate to TSV or TCV, except for \( \Delta T_{\text{air, BMS}} \) during cool transitions.

With classification based on BMS sensor readings, the neutral temperatures do not differ much between warm and cool transitions, both for \( T_{\text{air, current}} \) and \( T_{\text{air, previous}} \). The correlations of TSV with \( T_{\text{air, current}} \) and \( T_{\text{air, previous}} \) were stronger for warm transitions. The \( T_c \) values also did not significantly differ between warm and cool transitions (\( p = 0.24 \)).

Basing the classification on desk-sensor readings, the neutral temperature from TSV, \( T_{\text{air, current}} \), correlation was warmer for the warm transitions by 1.5 °C. The \( T_c \) values were significantly lesser for the cool transitions (\( p < 0.001 \)). Together, these findings imply that the cool transitions, paradoxically, evoked a warmer perception. Considering though that a slightly warm perception was found to be comfortable by

![Fig. 8. Scatter-plots of the temperature step recorded using desk-sensor and a) TSV and b) TCV. \( \Delta T_{\text{air, desk sensor}} > 0 \) is warm transition.](image)

![Fig. 9. Scatter-plots of the temperature step recorded using BMS sensor and a) TSV and b) TCV. \( \Delta T_{\text{air, BMS}} > 0 \) is warm transition.](image)

Table 4

<table>
<thead>
<tr>
<th></th>
<th>Warm Current</th>
<th>Warm Previous</th>
<th>Cool Current</th>
<th>Cool Previous</th>
</tr>
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<tbody>
<tr>
<td>TSV</td>
<td>0.40</td>
<td>0.02</td>
<td>&lt;0.001</td>
<td>21.8</td>
</tr>
<tr>
<td>TAV</td>
<td>0.35</td>
<td>0.04</td>
<td>0.49</td>
<td>0.004</td>
</tr>
</tbody>
</table>

the office occupants — as discussed earlier in Section 3.1.2 — this paradoxical perception need not have adversely impacted occupant opinion of the thermal environment.

4. Discussions

The survey covered two markedly different groups of participants who were from similar geographical and cultural background. Established thermal comfort standards have mostly originated based on research involving office workers or participants simulating office work. Transitions experienced by occupants across thermal zones in their workspace, as part of their schedule, have not been subjected to in-depth exploration. The current work intended to address this topic. Fortuitously, the investigation could cover a reasonably wide range of activity nature of the participants, it was considered suitable to analyse the collected data separately. During the study, we did not influence in any manner the default thermal conditions and temperature set-points within the buildings surveyed. Thus, the measured air temperature step changes mostly kept within ±2 °C. However, these values provide a realistic picture of in-use buildings.

Since participants filled up the survey responses mostly in the immediate wake of a transition, the analysis of thermal perception focussed on the air temperature steps and not on factors like clothing. Previous research also indicated the difficulty for participants to rate the humidity for small step changes [33]. Following the completion of surveys, since the responses were predominantly from female participants, in the age group of 20–40 (61%), age and gender related differences were not examined.

Comfort surveys in offices, with their “captive audience” are easier to conduct as opposed to the nurses who had to move around through their entire work day. It was also noted that during the second survey period, smaller number of responses were received from the nursing staff. This could imply a decreasing level of interest among the participants or it could also be due to the fact that the second observation period (during October and November) is typically a busier period for them. On a positive note though, responses in the second period were more complete, unlike during the initial survey period, when nurses often missed out on filling the locations across which the transition occurred. An option, which could provide nurses with some ease of handling the survey, may be using a cell phone app for questionnaire. All the while, any disruption to their regular work schedule and work environment must be avoided. We managed to be minimally intrusive by keeping in constant touch with the administrative authorities and the nurses themselves and taking into consideration their feedback in designing and executing the surveys.

In the office space, values of $T_{\text{air, BMS}}$ were significantly lower than $T_{\text{air, desk-sensor}}$ ($p < 0.001$, mean values of 21.8 vs 22.5 °C). This could be explained by the location of the desk-sensor being within the occupant’s micro-climate. This makes the air temperature sensor register local sources of warmth like the human body, personal computers, incoming solar radiation through the window etc., while care was taken not to expose it directly to radiant temperature. It was also noted that the subjective perception correlated in a similar manner to $T_{\text{air, BMS}}$ and $T_{\text{air, hallway}}$. This may be due to the fact that the BMS sensor is located near the entrance to the rooms, i.e., closer to the hallway than to the desk. This was also reflected in the differences observed when using $T_{\text{air, BMS}}$ vs $T_{\text{air, desk-sensor}}$ in interpreting occupant thermal perceptions. The discrepancy between $T_{\text{air, BMS}}$ and $T_{\text{air, desk-sensor}}$ advocates the need of appropriately locating BMS sensors for assessing the actual thermal condition faced by occupants, as was also found in a recent work [34].

Looking at warm and cool transitions, the perceptions evoked from the participants mostly did not have a significant difference. The only exception being the warm and cool transitions, based on $T_{\text{air, desk-sensor}}$, where the cool transitions were perceived to be warmer. This was a paradoxical finding we were unable to explain. However, it was noted that thermal perceptions correlated better to cool transitions in the hospital wards and to warm transitions in the offices. This supplements the findings of optimal thermal acceptability and thermal comfort for the two populations, which was slightly cooler for the care personnel and slightly warmer for the office personnel. The difference ultimately comes from the different activity profiles of the two groups. As would be expected [35], the more active group prefers a slightly cooler perception and the sedentary group, in a heating dominated climate, prefers slightly warm perception.

Transitions with a thermal step yielded better thermal acceptability for the nurses. In office, transitions with thermal steps lead to lower $T_c$ values based on $T_{\text{air, BMS}}$. This indicated a warmer perception associated with thermal steps. Since a slightly warm thermal sensation was found to be optimal in terms of TCV for the office occupants, it may be suggested that thermal steps may even have some beneficial aspects for thermal comfort perception for both populations. This is in accordance with previous observations that votes high on comfort scale are mostly elicited during transitions rather than in a steady thermal environment [36].

For the nursing staff, all responses taken together yielded a regression neutral temperature of 21.8 °C. This finding is similar to those in earlier studies where a mean air temperature of 21.5 °C, 21.8 °C, and 23 °C resulted in mean TSV values of −0.5 [37], −0.7 [26], and 1.05 [38], respectively.

For both groups, $\Delta T_{\text{air}}$ did not correlate to TSVs, except for the $\Delta T_{\text{air, BMS}}$. This would indicate that effect of transitions across air temperature differences ~ ±2 °C, if any, on thermal sensation were too short lived to be significant; especially, there does not seem to be any detrimental impact on TSV. The results thus are in line with findings from climate chamber studies, though the climate chamber studies [3] and outdoor–indoor transition studies [9] indicate that occupant thermal perception is not impacted across transitions of ±3 °C.

A discrepancy noted was that $\Delta T_{\text{air, BMS}}$ correlated with TSV for the office occupants. However, when a regression relation was attempted between $\Delta T_{\text{air, BMS}}$ and TSV, it did not satisfy the assumption of Skewness. So correlation apart, $\Delta T_{\text{air, BMS}}$ was not a predictor of TSV. From analysing the warm and cool transitions separately, it became apparent that the $\Delta T_{\text{air, BMS}}$ – TSV correlation may be primarily due to cool transitions.

A factor that could also be important in gauging transient perception would be thermal history/cultural background of the person, which we have not focused on in this study. Someone habituated to
buildings with cooler indoors may perceive a cooler transition differently than others. Similarly, occupants continually facing warm discomfort in their buildings could have different reaction to air temperature steps. This brings to fore thermal alliesthesia [39] and its possible occurrence across such regular transitions, involving small temperature deviations [40]. The pleasure associated with alliesthesia may thus be added to day-to-day experience using transitional zones.

A finding of import was regarding how thermal comfort considerations for hospital personnel strongly contrasts with those for office workers. The explanation is easy to come by: the completely different work profile for nurses. While the difference in their activity profiles makes the contrasts found fairly obvious, it is necessary to stress upon the importance of considering the nature of usage when designing a building for thermal comfort. Specifically, these differences do need to be considered more widely as part of thermal comfort design for health care professionals. Nurses, due to their higher activity rate, have different thermal comfort needs from patients [26]. Our results indicate that thermal steps within ±2 °C would not burden thermal perception of the nurses and might even improve it. Thus, zones other than patient rooms can be maintained at a lower air temperature to create a more comfortable environment for the nursing staff — as they transit through — and even possibly contribute to lowering heating energy demand. For the offices, on the other hand, looking at the preference for warmer conditions, the transitional use spaces — hallways, lobbies, stairways — can be maintained at a set-point lower than that of the office spaces, again making possible contributions to lowering heating energy use.

5. Conclusion

This work intended to examine the effect of spatial transitions within workplaces, across different thermal conditions, on occupant thermal acceptability. As observed from these two mixed methods surveys, following such transitions, when the air temperature differences were within ~ ±2 °C, occupant thermal perception was not impacted by the temperature difference of the transition. This was true for near sedentary office workers as well as more active nursing staff, in their routine work engagements. The transitions may even have had some beneficial impacts on thermal perception of both populations, the effect being more apparent for the nurses. Additionally, the comparative analysis of the two participant groups points us towards some stark differences in the needs of occupants based on their activity profile and purpose of the building. Specifically, the results draw attention to the contrasting thermal comfort needs of caregivers in hospitals.

Thermal perception from both groups indicates possible beneficial aspects of deliberate thermal zoning within these two types of buildings. Such zoning, when matched to the occupant activity profile and needs, can not only improve thermal comfort perception, but also provide possible advantages in terms of more flexible use of renewable energy. Since the data from climate chamber studies points to a breadth of transition of ±3 °C that does not affect occupant thermal perception, further studies would need to be performed to verify these broader limits under field conditions. Such studies would ideally also span across different time periods of the year and consider buildings with different use patterns.

Acknowledgement

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.buildenv.2018.08.049.

Nomenclature

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>BMS</td>
<td>Building Management System</td>
</tr>
<tr>
<td>ICMS</td>
<td>Indoor climate measurement stand</td>
</tr>
<tr>
<td>RH</td>
<td>relative humidity</td>
</tr>
<tr>
<td>TAV</td>
<td>Thermal acceptability vote</td>
</tr>
<tr>
<td>TCV</td>
<td>Thermal comfort vote</td>
</tr>
<tr>
<td>TSV</td>
<td>Thermal sensation vote</td>
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References