Indoor climate and thermal adaptation, evidences from migrants with different indoor thermal exposures

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Abstract

Previous adaptive thermal comfort research mainly emphasized the correlations between outdoor climate and thermal adaptation. In this paper, we explore the influence of indoor thermal experience on occupants’ thermal adaptation, especially with regard to physiological adaptation. We also investigate whether people with distinct cold indoor exposures have different levels of physiological adaptation to cold environment. A comparative experiment, including both physiological measurements and subjective questionnaires, was conducted in China where winter indoor climates in the northern region (with pervasive district heating) are much warmer than the southern region (without district heating). Two subject groups were recruited, namely: (a) N-N group - subjects who had lived in the northern China with district heating all their life, and (b) S-N group - subjects who grew up in the southern region without district heating but recently moved to the north. The results indicate that S-N subjects who had lived their entire lives in cold wintertime indoor climates had slither physiological response and felt less uncomfortable in mild cold exposures than N-N subjects who lived in neutral-to-warm wintertime indoor climates. The findings suggest that indoor thermal exposures can also influence occupants’ thermal adaptation, which can reserve as a reference to the future adaptive thermal comfort model.

Keywords: adaptive thermal comfort; physiological adaptation; thermal history; indoor thermal environment; thermal health

1 Introduction

Indoor environment quality is strongly correlated with people’s comfort perception, wellbeing and work performance (Zhu and Luo, 2015). Questions such as ‘what kind of indoor climate should be created’ and ‘how to create it’ always capture building environment researchers’ attention. Considering the increasing amount of energy that is consumed by HVAC services in large economic entities, it is essential to review the status of current indoor climate and shape its future roadmap.

1.1 The warming winter-time indoor temperatures

Since the application of HVAC technologies in buildings, people have the ability to control the indoor thermal environment freely. The rapid development of HVAC engineering technologies coupled with the increase in affordability enable us to create constant and uniformly neutral indoor thermal conditions easily by just pressing several buttons. A study from (Davis and Gertler, 2015) described the growing use of air conditioning in developing nations. Covering our homes, workplaces and transport, pervasive HVAC equipment seems to have become necessity for modern life. Not surprisingly, indoor climates in modern buildings are moving ever-closer to theoretically ideal conditions around thermal neutrality.
Figure 1 shows the temporal trends of wintertime indoor residential temperatures in countries such as the US, the UK, northern Japan and China. Compared with the situation a century ago, our wintertime residential temperatures were climbing and converging to the neutral comfort zone of about 20°C. Similar phenomena also happened in other developed countries like Denmark, France, Germany, Italy etc. (Mavrogianni, 2013). Some researchers even named this warming trend of wintertime indoor temperatures as ‘homogenization of built environment’ and ‘comfort capsules’ (Wilhite, 2009). Moreover, Figure 1 also reveals a ‘knotty’ problem in Chinese residential space heating. The wintertime residential indoor temperature gap between northern and southern China (refer to the Hot Summer and Cold Winter climate zone of China) is ‘huge’. In recent years, more and more people in south part of China have been requesting space heating in residential buildings to improve their living standards. Many efforts have been made to deal with this problem.

**Figure 1 Long-term trends of wintertime residential temperatures in the UK, the US, northern Japan and China**

1.2 Statement of the problem: indoor climate and thermal adaptation
Both the indoor warming drift posed in Figure 1 and huge wintertime indoor temperature gap between southern and northern China beg the question as to whether long-term indoor thermal experience would shift occupants’ thermal comfort perception. Although previous adaptive research has managed to shed some useful light on how occupants adapt to thermal environments, the evidence relevant to the driver of thermal adaptation (indoor or outdoor thermal exposures?) has mostly been anecdotal. If we carefully look into existing adaptive models adopted in current standards, all of them simply utilized prevailing outdoor temperatures as the parameter to represent thermal history, which means they all regarded outdoor climates as the only adaptation driver. However, what about the influence of indoor thermal exposures on thermal adaptation? People spend most of their time living in indoors. There is no reason to ignore the influence of indoor thermal exposures.

1.3 Objective
This study focuses on the impacts of indoor thermal exposures on occupants’ physiological adaptation, and ask the question whether people with distinct cold indoor exposures have different levels of thermal adaptation to cold thermal environment.
2 Materials/Methods
2.1 Subjects recruitment
Two subject groups with distinct indoor thermal histories were recruited on the basis of their wintertime indoor thermal exposures (Table 1). N-N group consists of subjects who had spent their entire life in the heated northern region with neutral-to-warm wintertime indoor climates (with space heating both at home and school dormitory). S-N group consists of subjects selected from those who grew up in the hot summer and cold winter climate zone without space heating facilities (no space heating both at home and school dormitory) and recently moved to north. Each group contains 15 healthy volunteers who did not know much about thermal comfort and had no smoking habit. All the subject were asked to do some physiological measurements and subjective response in a climate chamber. To exclude the influence of gender, age, weight and etc., all the subjects were male college students. Table 1 summarizes their profiles. Although the N-N subjects had slightly higher heights, their BMI indexes were controlled in normal range and were very close to S-N group.

<table>
<thead>
<tr>
<th>Group</th>
<th>Description</th>
<th>Sample size</th>
<th>Age (year)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>BMI</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-N</td>
<td>grow up in cold climate zone with district space heating</td>
<td>15</td>
<td>20.5±1.3</td>
<td>176.3±6.2</td>
<td>65.6±4.9</td>
<td>21.1±1.1</td>
</tr>
<tr>
<td>S-N</td>
<td>grow up in hot summer and cold winter climate zone without district space heating</td>
<td>15</td>
<td>18.8±0.7</td>
<td>171.9±3.3</td>
<td>63.3±4.5</td>
<td>21.6±1.2</td>
</tr>
</tbody>
</table>

2.2 Experimental protocol
Figure 2 shows the detailed experiment protocol. When the experiment began, subjects had 10 min to calm down, change clothes, learn how to vote, as well as to wear physiological sensors. All the subjects were required to wear uniform clothes (underwear, T-shirt, shorts, socks, and sport shoes) with a total clothing insulation of 0.42clo. The reason that we chose light dress mainly lies in the convenience to wear physiological sensors. Then, the subjects were asked to stay in a neutral temperature (26°C) for 30 min. Both physiological measurement and subjective questionnaire were started from the beginning of this phase. Finally, the subjects moved to other cold cases (24/21/18/16°C) for 60 min.

To ensure the validity of experimental data, subjects were reminded to avoid caffeine, alcohol, smoking and strenuous activities, and to sleep well in the day prior to the experiment. At the beginning of recruitment, voluntary subjects were informed that there would have some cold exposures and that they were free to interrupt the experiment at any time if they felt unwell. For each subject, the temperature cases were ordered randomly.
Physiological parameters such as metabolic rate, skin surface blood flow rate, skin temperature, and heart rate were monitored as well. The time to measure these physiological parameters has been illustrated in Figure 2. For metabolic rate determination, the Vmax Encore metabolic cart (SensorMedics, USA) was utilized to measure the oxygen consumption and carbon dioxide production of the human body. Heart rate was monitored by Equivital heart rate measurement (Hidalgo, UK) during the whole 90 min experimental period. Skin surface blood flow rate was measured by PeriFlux 5001 (Perimed, Sweden). Skin temperatures were measured during the entire 90 min exposure by Vitalsense Dermal Patch sensors with a precision of 0.1 °C (Respironics, USA). The sensors were attached at nine body areas: forehead, chest, back, upper arm, forearm, hand back, thigh, calf, and ankle. The mean skin temperature was calculated using the following equation:

\[ T_{ms} = 0.077T_{forehead} + 0.18T_{chest} + 0.18T_{back} + 0.077T_{forearm} + 0.077T_{upper\ crus} + 0.05T_{hand\ back} + 0.19T_{thigh} + 0.19T_{caif} + 0.19T_{ankle} \]

To collect subjective responses, subjects were asked to vote every 5 min. The questionnaire includes a seven-point thermal sensation vote (TSV), a seven-point thermal comfort vote (TCV), self-reported shivering or sweating rate, and other miscellaneous information. To compare the data from different cases, Independent Samples T Test and Paired-Samples T Test were utilized. When the test result shows significance of difference, it is labeled as ‘p<0.05’ or ‘p<0.01’, otherwise, ‘p>0.05’ was labeled.

3 Results
3.1 Physiological response
Figure 3 compares the physiological response between N-N group and S-N group. The data includes results from the steady state of each temperature case. In general, when
temperature dropped from 26°C to 16°C, the average metabolic rate increased nearly 14%, the mean skin temperature dropped from 33.8°C to 30.9°C, the average blood flow at left middle fingertip decreased from 350 unit to 213 unit, while the heart rate did not show significant changing.

Further comparing the differences between the two subject groups, it can be seen that no significant difference exists in metabolic rate and heat rate. However, the mean skin temperature and blood flow showed some differences between these two groups. Especially in mild cold conditions (21°C and 18°C), S-N subject group had higher mean skin temperature and higher blood flow. In conditions close to thermal neutrality (26°C and 24°C) and intolerable cold temperature (16°C), no significant differences were found.

Figure 3 Physiological response differences between N-N group and S-N group: a) metabolic rate, b) mean skin temperature, c) blood flow at left middle fingertip, d) heart rate

Figure 4 illustrates the changing process of mean skin temperature in different experimental cases. Mean skin temperature decreased with the drop of ambient temperatures. In 21°C and 18°C cases, N-N subject group had slower skin temperature decreasing rate during the adjusting process and lower skin temperature after reaching steady state. Similarly, the differences only exist in 21°C and 18°C cases. No significant differences were observed in other temperature cases.
3.2 Subjective perception

Figure 5 compares the subjective thermal sensations and comfort perceptions between N-N group and S-N group. The data includes results from the steady state of each experimental case. Compared with N-N group, S-N group felt less cold and less uncomfortable when they were exposed to mild cold conditions (21°C and 18°C). In other neutral temperatures (26°C and 24°C) and intolerable cold case (16°C), no significant differences between these two groups were found.
4 Discussion

4.1 Physiological adaptation to cold

Figure 6 further summarizes the regression line of average metabolic rate and temperatures. The metabolic rate in 16°C were 13.6% higher than that in neutral case. And this increasing trend happened in both N-N and S-N group. It is noteworthy that N-N subjects reported higher shivering rate (which is closely related with human body heat production) in 21°C and 18°C, while there was no significant difference in metabolic rate between these two groups.

What is the underlying mechanism behind this phenomenon? Some recent research conducted by van Marken Lichtenbelt’s group reported a kind of fat called “brown adipose tissue” (van Marken Lichtenbelt, 2009). The brown adipose tissue is closely related with cold-induced non-shivering thermoregulation (thermogenesis in the absence of shivering) of human body. Their research results indicated that cold exposure would increase brown adipose tissue mass and activity (van Marken Lichtenbelt, 2009). According to their findings, S-N subjects may have increased brown adipose tissue mass and activity, because they lived in colder wintertime indoor temperatures. And this might be the reason why S-N subjects had higher shivering rate but the same metabolic rate with N-N subjects. However, it should be noted that this inference needs to be further confirmed.

\[
y = 0.0644x^2 - 3.6603x + 112.48
\]

\[R^2 = 0.9998\]

Figure 6 Increasing trend of average metabolic rate and self-reported shivering rate

4.2 Indoor cold exposure and comfort perception

Figure 7 further compares the regression lines of mean TSV and PMV. rPMV was revised PMV by using the measured metabolic rate in each temperature case. Firstly, the slope of TSV regression line for S-N group is slighter than that for N-N group, which indicates that S-N subjects felt less cold than N-N subjects did. This results is consistent with the physiological test introduced above. Normally, a colder TSV corresponds to lower skin temperature, lower skin surface blood flow rate, higher metabolic rate, and higher self-reported shivering rate. All this results collectively point to a conclusion that subjects with colder indoor exposures had slighter physiological response and felt less uncomfortable in mild cold conditions. Secondly, the “scissors difference” (different slopes of regression lines) between PMV and TSVs indicates that PMV overestimated subjects’ cold sensations. This may be resulted from the inaccurately assumed metabolic rate (1.1 met). If the actual measured metabolic rates were utilized, the rPMV was quite close to the TSV from N-N group. This phenomenon reminds us to consider metabolic rate more carefully in future comfort studies. However, it should be noted that rPMV still overestimated the actual sensations of S-N group.
5 Conclusions

Human body itself can adapt to cold environment to some extent. At 16°C, the metabolic rate increased 13.4% referring to the value at 26°C. The self-reported shivering rate also increased drastically in cold exposures. The skin surface blood flow and skin temperature decreased with the drop of ambient temperature.

Subjects acclimated to cold indoor climate had slighter physiological response and felt less uncomfortable during mild cold exposure. In 21°C and 18°C cases, S-N subjects had higher skin surface blood flow and higher skin temperature than N-N subjects did. And S-N subjects felt less cold and less uncomfortable.

Acknowledgement

This study was funded by Innovative Research Groups of the National Natural Science Foundation of China (51521005) and the Natural Science Foundation of China (51308396 and 51508300).

References


