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Thermal comfort chamber study of Nordic elderly people with local cooling devices in warm conditions

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Elderly people
Local cooling devices
Climate chamber
Warm environment

ABSTRACT

In this study, we investigated the thermal response of Nordic elderly people before and after using local cooling devices in warm conditions. A climate chamber was used to simulate warm environments. We studied three types of local cooling devices: a table fan, an evaporative cooling device, and an air-cooled jacket. A total of 26 elderly participants were recruited for this study. During the experiments, votes of thermal and air movement perception were collected. The elderly voted for a neutral temperature of 26 °C, preferred temperature of 26.5 °C, and an acceptable temperature of 28 °C. Local thermal sensation in the torso areas of the elderly affected their overall thermal sensation more than local thermal sensation in the extremities under warm conditions. When the ambient temperature was risen to 1 °C and 4 °C higher than 26 °C, the behavior pattern of using local cooling devices for the elderly was: 1) with the small rise the use rate reached 50% with the lower speed modes mainly chosen; and 2) the higher rise caused more people to choose higher speed modes. Our findings show that the three local cooling devices can increase thermal acceptability under warm conditions. More than 80% of elderly accepted the 28 °C thermal environment, and less than 80% accepted 32 °C. The acceptance rate for air movement after using devices was decreased and less than 80% in most conditions. Moreover, all devices performed better under low-humidity conditions.

1. Introduction

Global average surface air temperatures are estimated to rise by approximately 4 °C by the end of the twenty-first century [1]. This global warming trend can result in heat waves and frequent extreme weather conditions. The positive relationship between heat exposure and mortality has been well established worldwide [2]. Polar amplification in northern latitudes makes northern Europe more susceptible to global warming [3]. In Finland, Jokisalo et al. examined room temperatures of Helsinki apartment buildings during the summer [4], and found that the temperature in 80% of rooms was higher than 27 °C during the 2018 heat wave, and the highest indoor temperature reached 32.8 °C in 2019, which is higher than the 32 °C limit set by the Ministry of Social Affairs and Health [5].

People spend more and more time indoors, and therefore, maintaining indoor health and comfort has become an important task. The thermal response of humans is affected by numerous factors, including gender, age, climate zone, country, and thermal history [6–8]. Age is a particularly concerning factor because the world’s population is estimated to increase from 6.1 to 9.7 billion between 2000 and 2050, with the elderly proportion of the population (those over 60 years old) increasing from 10% to 21.8% [9,10]. Global warming exacerbates the difficulties faced by aging societies. Increased cardiovascular strain caused by heat stress is an important health concern during hot weather [11]. In several countries, older adults with heart problems experienced a higher risk of heat-related mortality than younger adults [12–16]. Sohail et al. [17] found that heatwaves pose a risk of heat-related morbidity in northern climates.

The indoor environmental design standards used now [18–20] are not necessarily applicable to the local elderly for two main reasons. First, present standards are based on average adults even though numerous studies have investigated the differences in thermal comfort between young and elderly people [7,21–24]. Researchers [25,26] concluded that the elderly have a narrower acceptable temperature range in a stable environment, while in a transient environment, they are less

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sensitive to environmental changes, which makes them more vulnerable in extreme environments. Furthermore, these standards apply to widespread areas, but Wang et al. [27] found that local climate has the most significant effect on people’s neutral temperature and thermal sensitivity. Therefore, it is necessary to conduct thermal comfort experiments in different climate zones to determine environmental standards suitable for the local elderly population.

In addition to the adverse effects of declining physiological functions, the elderly also face problems of “fuel poverty” caused by declining incomes [25]. Air conditioning is the traditional method for lowering the temperature of an indoor space during hot weather but it consumes a large amount of energy [28]. The operating and maintenance expenses of air conditioners are prohibitively high for numerous elderly people [29,30]. Moreover, because the elderly may have difficulty understanding the controls, proper operation of the air conditioners is not guaranteed [31,32]. As an alternate solution, thermal comfort can be achieved by creating a microclimate surrounding the human body that cools certain body parts [33,34]. Changes in the local thermal sensation might result in varied overall thermal sensations under the same conditions [35]. Certain studies [36–39] calculated the local thermal sensation weighting factor for each body part in relation to the overall thermal sensation. The results showed that the lower body had a smaller effect on overall thermal sensation than the upper body. Therefore, cooling the head and upper body in warm and neutral climates would be effective. However, the participants in these studies were often young adults, and little research has been conducted on the elderly.

Devices controlled by individuals to create a microclimate directly surrounding the occupant for ensuring thermal comfort are called Personal Comfort Systems (PCS). PCS have the potential to meet individual comfort needs while reducing the overall energy consumption in buildings [40]. Some studies have evaluated [40–42] and analyzed the effects of PCS with different powers, locations, and types on thermal comfort [43–47], and proposed some indices based on thermal perception, such as “Corrective Power”, to describe the effect of various PCS [40]. Although Ravanelli et al. [48] demonstrated the benefits of fans for young adults during simulated heatwave conditions, Gagnon et al. [49] could not obtain the same conclusion in the corresponding experiment with elderly people, indicating the difference in the effects of fans for young and elderly people. Furthermore, air-cooled garments regulate the microclimate between the human body and the clothes by increasing the air velocity, promoting evaporative heat loss, and effectively reducing heat strain [50,51]. In addition to a variety of fans that enhance airflow, numerous new devices for lowering the supply air temperature, such as evaporative cooling devices, have been introduced [52]. Tejero-González et al. [53] demonstrated that evaporative cooling devices can substantially improve thermal comfort in open office spaces. These devices are low-power, easy-to-use, and efficiently ensure human thermal comfort under certain conditions. Currently, relevant studies on how local cooling devices improve thermal comfort for the elderly are lacking. Some studies have recorded user behaviors and established usage models [34,43,54–57] but the majority of these studies focused on young people in office buildings and only a few studied the elderly. Most data were obtained from field studies, which may include confounders. Research on elderly people’s behavior can act as a reference for future smart residential or nursing homes, promote healthy aging, and model the implications of these devices for the elderly.

First, based on authors’ knowledge, existing research on elderly people’s thermal comfort [21–32] has been conducted in many other regions, but not in the Northern Europe region, which has a different climate. Local climate significantly influence people’s neutral temperature and thermal sensitivity. Thus, this study estimated the neutral, preferred, and acceptable indoor air temperature for the elderly in Finland, as well as their thermal sensation weighting factors in different body parts. Second, there are studies on the effect of fans [40–49]; however, there is no research on the effect of evaporative cooling devices and air-cooled jackets on the comfort of the elderly in the current literature. Therefore, this study analyzed the psychological changes of the elderly after using these devices based on thermal perception and air movement perception. Furthermore, most research on the device-use behavior of the elderly are field studies [34,43,54–57], rendering device usage prone to being influenced by confounders. Thus, this study constructed a device usage model and evaluated the device’s effective coverage via climate chamber tests in which the elderly only use local cooling devices to meet their thermal comfort.

The novelty of this study is to examine the thermal comfort of elderly people in the Nordic region and the contribution of different local cooling devices in warm conditions. Moreover, this work describes for the first time how elderly people utilize the evaporative cooling device and an air-cooled jacket. This entire work provides guidance for local indoor environmental codes and contributes to the design of future intelligent nursing homes.

2. Method

2.1. Laboratory facilities

2.1.1. Climate chamber

This experiment was conducted in a climate chamber. The climate chamber was 5.5 m long, 3.8 m wide, and 3.2 m high and located in a laboratory hall. It comprised of a diffuse-ceiling ventilation system, heated simulation windows, and humidifiers (Fig. 1). Ventilation air was supplied through 14-mm diameter nozzles drilled along the ceiling panels, which covered the entire ceiling. The perforation rate of the panels was 0.50 ± 0.02%. The walls comprised seven heated windows (0.6 m × 1.79 m each). The temperature of the heated windows was controlled using a water system. Four automatically controlled humidifiers, providing steam at a temperature equal to indoor air temperature, were in the middle of the side with the heated windows. Three sets of a table with a computer and a chair were arranged on the side opposite to the windows and were separated by partition walls.

The air temperature (T_a) and relative humidity (RH) of Finland’s typical summertime and heat wave periods were used to determine the five experimental conditions [58]: T_a = 26 °C, RH = 40%; 29 °C, 40%; 28 °C, 60%; 33 °C, 40%; and 32 °C, 50%. Previous research [59] estimated that in Finland in 2050, rooms without cooling systems will experience more hours above 32 °C, whereas rooms with ventilation

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAV</td>
<td>Air movement acceptance vote [-]</td>
</tr>
<tr>
<td>ADV</td>
<td>Air movement disturbance vote [-]</td>
</tr>
<tr>
<td>APV</td>
<td>Air movement preference vote [-]</td>
</tr>
<tr>
<td>ASV</td>
<td>Air movement sensation vote [-]</td>
</tr>
<tr>
<td>Eva</td>
<td>Evaporative cooling device [-]</td>
</tr>
<tr>
<td>Fan</td>
<td>Table fan [-]</td>
</tr>
<tr>
<td>HM</td>
<td>Higher modes [-]</td>
</tr>
<tr>
<td>Jac</td>
<td>Air-cooled jacket [-]</td>
</tr>
<tr>
<td>LM</td>
<td>Lower modes [-]</td>
</tr>
<tr>
<td>MS</td>
<td>Multiple sclerosis</td>
</tr>
<tr>
<td>Pa</td>
<td>The proportion of device adjustments in a period [%]</td>
</tr>
<tr>
<td>RH</td>
<td>Relative humidity [%]</td>
</tr>
<tr>
<td>Ru</td>
<td>The use rate of the device in a period [%]</td>
</tr>
<tr>
<td>SBS</td>
<td>Sick building syndrome [-]</td>
</tr>
<tr>
<td>Ta</td>
<td>Air temperature [°C]</td>
</tr>
<tr>
<td>TAV</td>
<td>Thermal acceptance vote [-]</td>
</tr>
<tr>
<td>TCV</td>
<td>Thermal comfort vote [-]</td>
</tr>
<tr>
<td>TPV</td>
<td>Thermal preference vote [-]</td>
</tr>
<tr>
<td>TSV</td>
<td>Thermal sensation vote [-]</td>
</tr>
</tbody>
</table>
systems will experience more hours above 27 °C. Consequently, these five test conditions were representative. Throughout this paper, RH is denoted by (T) and (H) for typical RH (40%) and higher RH (50% or 60%), respectively. Furthermore, each test condition was named using a combination of Ta and RH (Table 1).

This study estimates the influence of Ta and RH on the thermal comfort of the elderly, to find their neutral and preferred temperatures. Even in practice, these parameters varied a lot. Thus, in this study, the indoor Ta and RH were fixed to evaluate the role of different local cooling devices in maintaining the thermal comfort of the elderly. In the climate chamber, Ta was controlled by balancing the heat gain. Supply air temperature was 17 °C, approximately 10 °C lower than the room air temperature during maximum heat gain [59]. Overall heat gain during the experiment included the heat gain from human subjects, lighting systems, computers, and heated simulated windows. Three heated dummies (cylindrical heat sources with 0.4-m diameter and 1.1-m height) were also used to balance the heat loads and were placed in front of the heated window side. Our study included three human subjects in each test, and in case participants were missing from a test, dummies were used to replace their heat gain and maintain a constant Ta. Input parameters were calculated based on the heat balance required to reach the target Ta. Details of the operating settings for the five experimental conditions are summarized in Table 1. The Standard EN15251 Category B for low-polluting buildings has set the ventilation airflow rate at 2 L/(s, m²), which was the basis for this study. The airflow rate was constant at 42 L/s.

2.1.2. Local cooling devices

This study used the following local cooling devices: (a) table fan, (b) evaporative cooling device, and (c) air-cooled jacket (Fig. 2(a)(b)(c)). The table fan was 230 mm in diameter with three blades. It had two speeds and an electric power range of 0–25 W. The air-cooled jacket, designed to be worn over clothing, consisted of a spacer vest liner with an impermeable outer layer, two 97-mm wide fans placed symmetrically on the lower back, an internal pocket for a rechargeable battery, and weighed 0.7 kg. The bottom of the jacket was sealed off with a ring of elastic material, allowing air to escape only through the top. When in use, the fans were activated simultaneously to supply ambient air to the torso. It had four speeds and an electric power range of 0–20 W. The evaporative cooling device was 180 mm × 180 mm × 182 mm. It had a medium that was humidified via capillary action using water from a small side tank (1000 mL) and a small fan with 10 speeds and an electric power range of 0–10 W.

The table fan and evaporative cooling device were fixed to Table 1 m away from the subject (Fig. 2(d)). The device angle was adjusted such that airflow was directed toward the torso rather than the head to minimize unwanted symptoms, such as dry eyes and headaches. The jacket size (small, medium, or large) was selected based on the participant’s body size.

2.2. Participants and training session

This study was approved and supported by the Aalto University Research Ethics Committee (D/793/April 03, 2021, approved on Sep 23rd, 2021). Participants were required to be free of multiple sclerosis (MS), Parkinson’s, kidney disease, or previous paralysis or heart attack. Furthermore, participants with age-related memory impairments were excluded because it was difficult for them to comprehend the study. Finally, 26 native elderly Finnish individuals were recruited. The anthropometric data of the participants are presented in Table 2.

The participants underwent a training session before the test. During this session, precautions and experimental procedures were explained to the participants. The experimental precautions included: 1) Evasion from alcohol or coffee consumption within the 24 h before the experiment; 2) Wearing short-sleeved T-shirts, trousers, socks, and shoes (0.5 clo) for all the tests; the clothing should not be loose enough to hinder wearing the air-cooled jacket; and 3) Participants could drink but not eat during the test periods. In the climate chamber, the subjects were provided with a bottle of water placed in advance on the desk. 4) Participants were not allowed to communicate with each other about the experiment during the test. During the training session, the researcher explained in detail the procedures of completing the questionnaires used during the experiment and use of the three local cooling devices. Each participant participated in the experiment once a week for five weeks. The number of participants in each test condition varied because not every participant could participate in the experiment on time. The number of participants in the different cases is shown in Table 2.

2.3. Measurements

2.3.1. Indoor environment parameters

TinyTag 2 plus data loggers (air temperature accuracy: ±0.5 °C, relative humidity accuracy: ±3%) were used to monitor Ta and RH (Fig. 1). Sensors attached to the chair were placed on the back of the
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Fig. 2. Local cooling devices and their positions: (a) table fan, (b) air-cooled jacket, and (c) evaporative cooling device. (d) The placement of table fan and evaporative cooling device on the table.

Table 2
Anthropometric data of the elderly participates and attendance in the five conditions.

<table>
<thead>
<tr>
<th>Case</th>
<th>Number of participants</th>
<th>Anthropometric units (Mean ± SD)</th>
<th>Male (7)</th>
<th>Female (19)</th>
</tr>
</thead>
<tbody>
<tr>
<td>26 °C</td>
<td>26</td>
<td>Age (year) 70.9 ± 70.8</td>
<td>5.5</td>
<td>6.0</td>
</tr>
<tr>
<td>29 °C</td>
<td>24</td>
<td>Height (cm) 177.7 ± 161.8</td>
<td>4.0</td>
<td>4.6</td>
</tr>
<tr>
<td>28 °C</td>
<td>26</td>
<td>Weight (kg) 78.5 ± 67.6</td>
<td>8.7</td>
<td>9.6</td>
</tr>
<tr>
<td>32 °C</td>
<td>20</td>
<td>Waist circumference (cm) 95.3 ± 94.0</td>
<td>7.3</td>
<td>11.3</td>
</tr>
<tr>
<td>32 °C</td>
<td>23</td>
<td>Neck circumference (cm) 39.7 ± 35.6</td>
<td>1.5</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Table 3
Measured environmental parameters in five conditions.

<table>
<thead>
<tr>
<th>Case</th>
<th>Test sequence</th>
<th>Test conditions (Mean ± SD)</th>
<th>Enthalpy (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>26 °C (T)</td>
<td>2</td>
<td>25.7 ± 0.5 °C 42 ± 2%</td>
<td>47.8</td>
</tr>
<tr>
<td>29 °C (T)</td>
<td>5</td>
<td>29.0 ± 0.5 °C 42 ± 3%</td>
<td>56.0</td>
</tr>
<tr>
<td>28 °C (H)</td>
<td>3</td>
<td>28.3 ± 0.5 °C 62 ± 5%</td>
<td>66.7</td>
</tr>
<tr>
<td>33 °C (T)</td>
<td>1</td>
<td>32.6 ± 0.4 °C 38 ± 2%</td>
<td>62.7</td>
</tr>
<tr>
<td>32 °C (H)</td>
<td>4</td>
<td>31.7 ± 0.6 °C 48 ± 3%</td>
<td>67.9</td>
</tr>
</tbody>
</table>

2.3.2. Questionnaire survey

This experiment utilized two types of questionnaires to record the psychological parameters of the participants: long and short, as shown in Table 4. The long questionnaire elicited responses regarding participants’ overall thermal perception (thermal sensation, thermal comfort, thermal preference, and thermal acceptance) and overall air movement perception (air movement sensation, air movement preference, air movement acceptance, and air movement disturbance). Meanwhile, this questionnaire included questions about local thermal sensations (forehead, chest, pelvis, upper back, lower back, forearm, palm, thigh, calf, and foot). Additionally, some symptoms chosen from common sick building syndrome (SBS) were also listed in the long questionnaire. Due to time limitations, this study did not ask about local air movement sensation, but rather concentrated on local thermal sensation to avoid fatiguing the participants. The short questionnaire only asked overall thermal sensation, thermal comfort, thermal acceptance, air movement sensation, and air movement disturbance.

Table 4 specifies the questions and scales used. The participants responded to the questions by marking on a continuous scale. Participants could indicate intermediate values (0 or “neutral feeling”) when responding to questions about thermal sensation, but not for questions about thermal comfort and acceptability. This is because an individual cannot be comfortable and uncomfortable, and the thermal conditions cannot be acceptable and unacceptable at the same time.
2.4. Test procedure

The experimental process is illustrated in Fig. 3. The participants arrived at the lab 25 min before the test and changed their clothing. In the preconditioning phase, test participants were asked to remain sedentary for 40 min to adapt to the test environment, during which they could use a computer or read. Subsequently, in the local cooling phase, participants were permitted to vary the operation mode of the given local cooling devices according to their own preference, but not the position or angle of the table or evaporative fans. The following four phases were repetitions of the first two, where subjects sat for 40 min before modifying the settings of the device for another 40 min. The three participants changed seats at the end of each local cooling phase to ensure that they used all three devices.

To ensure participant health, a nurse measured the participants’ heart rate and ear temperature after each 40-min sedentary phase. To explore the elderly’s psychological responses, the participants were asked to complete a long questionnaire during the final 5 min of each phase and two short questionnaires at the 20th and 30th min of each local cooling phase. To explore their usage behavior, participants were asked to record their device usage patterns in the questionnaire every time they changed the mode in each local cooling phase.

During the experiment, participants’ skin temperatures were also measured by iButton sensors (Maxim Integrated, USA, air temperature accuracy: ±0.5 °C) every minute. However, due to the paper length limitation, this study focused on analyzing subjective votes and behaviors.

2.5. Data analyses

Pearson correlation analysis was applied to determine the correlation between thermal environmental parameters and psychological votes from questionnaires, and then linear regression was used to build relationships between them.

This experiment was a within-subject research with various testing conditions and devices. For each device, under each condition, each participant had a steady phase (preconditioning or rest phase) and a local cooling phase; thus, a paired t-test was applied to compare the votes between steady phase and local cooling phase. Further, under each condition, participants voted in each steady phase (three in total), while they voted three times in each local cooling phase. Therefore, the psychological parameters were compared using a repeated-measures ANOVA (Greenhouse–Geisser adjustment) with local cooling conditions as the independent variable. Shapiro-Wilk test was used to determine normal distribution.

Statistical analyses were performed using SPSS 20.0 and Origin Pro. Results were considered statistically significant at \( p < 0.05 \), "*" and "**" indicates a significant difference of \( p < 0.05 \) and a highly significant difference of \( p < 0.01 \), respectively.

A weighting factor method was used to specify the relationship between local thermal sensation and overall thermal sensation. To avoid multicollinearity between local thermal sensations of each body part, this study used the Principal Components Analysis (PCA) to extract some uncorrelated eigenvectors from the related matrix of local thermal sensations first, and then used multiple regression to build the model between overall thermal sensation and these eigenvectors [60].

Logistic regression, as a common method for analyzing binary response variables, can be used to describe the relationship between environmental parameters and device usage. Ordinal regression analysis is the extension of binary logistic regression, which could be used when the categorical variable has more than two levels with ordinal nature. Since each device has several ordinal speeds, this study used Ordinal regression analysis to further explore the usage pattern. Nagelkerke’s pseudo \( R^2 \) was applied to evaluate the goodness-of-fit of the model.

3. Results

Section 3.1 analyzed the psychological changes during the steady phases, and Section 3.2 presents the behavior and psychological changes of participants after using different local cooling devices in local cooling phases.

3.1. Psychological changes in preconditioning and rest phases

Each test condition comprised three steady periods before the actual local cooling device tests: a preconditioning phase and two rest phases. A repeated-measures ANOVA was performed, yielding no significant differences \( (p > 0.05) \) among the three steady phases. This suggests that the participants can be considered to have adapted to the environment in the last 5 min of each steady phase. Therefore, the analysis in Section 3.1 used data from all three steady phases.

3.1.1. Thermal perception and air movement perception

The thermal perception of the elderly was analyzed using thermal comfort votes (TCV), thermal sensation votes (TSV), thermal preference vote (TPV), and thermal acceptance vote (TAV)

Thermal perception was significantly correlated with \( T_a \) and \( RH \) \( (p < 0.05) \), and the linear regression results, which was derived from all individual thermal perception vote in steady phases, were listed in Table 5. Fig. 4 illustrates these correlations with distinct lines, and depicts the mean values of TSV, TCV, and TPV in test conditions with distinct dots. When RH was 50%, the \( T_a \) at which TSV = 0 was 26.1 °C, \( T_a \) at which TCV = 0 was 25.9 °C, and \( T_a \) at which TPV = 0 was 26.5 °C. A

<table>
<thead>
<tr>
<th>Linear regression</th>
<th>Formula</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCV</td>
<td>(-9.469 + 0.325 \times T_a + 0.020 \times RH)</td>
<td>0.54</td>
</tr>
<tr>
<td>TSV</td>
<td>(-9.180 + 0.324 \times T_a + 0.016 \times RH)</td>
<td>0.51</td>
</tr>
<tr>
<td>TPV</td>
<td>(10.549 - 0.366 \times T_a - 0.017 \times RH)</td>
<td>0.46</td>
</tr>
</tbody>
</table>

Table 5: Factors in different formulas under different room air relative humidity conditions, where \( T_a \) is expressed °C and RH in %

![Fig. 3. Schedule of the experiment. (L = long questionnaire; M = Measurements; S = short questionnaire; C = change seats).](image-url)
neutral $T_a$ of $26 \degree C$ was comfortable for the elderly, but they preferred an environment slightly warmer by $0.5 \degree C$. The effect of RH was smaller than that of $T_a$. With a 25% increase in RH, TSV, TCV, and TPV changed by approximately 0.5 scales.

The absolute values of TSV, TCV, and TPV at $33 \degree C$ (T) were lower than those at $32 \degree C$ (H) (Fig. 4). This study speculated that this may be caused by a change in the main heat dissipation method. Sensible heat dissipation was the main method for elderly people when the $T_a$ was approximately $29 \degree C$. As $T_a$ increased, sensible heat dissipation weakened, and the primary mode of heat dissipation may shift to evaporative heat dissipation (visible and latent sweat evaporation). Temperature of $32 \degree C$ (H) had a higher RH of 50%, whereas $33 \degree C$ (T) had 40%. When the ambient temperature or water vapor pressure exceeds a threshold, evaporative heat dissipation of the human body increases rapidly, which might slow overall heat dissipation [61].

Fig. 4 depicts the TAV proportion in the various ranges (TAV $>$ 1, 0 $<$ TAV $\leq$ 1, $-1$ $\leq$ TAV $<$ 0, and TAV $<$ $-1$) using stacked columns. If we regard TAV ranging between 0 and 3 as representing feelings of “acceptable”, then the proportion of participants who accepted the thermal condition at $26 \degree C$ (T), $28 \degree C$ (H), $29 \degree C$ (T), $32 \degree C$ (H), and $33 \degree C$ (T) was 93%, 76%, 73%, 24%, and 42%, respectively, indicating that a combination of high $T_a$ and high RH was less acceptable for the elderly. The environment was generally considered to be satisfactory when approximately 80% or more of the occupants accept the environment [18]. Thus, the upper limit $T_a$ accepted by the elderly in this study was approximately $28 \degree C$.

The air movement perception of the elderly was analyzed using the air movement sensation vote (ASV), air movement preference vote (APV), and air movement acceptance vote (AAV).

Air movement perception was significantly correlated with $T_a$ ($p < 0.01$) (Fig. 5). An increase in $T_a$ decreased ASV and increased APV. When $APV = 0$, ASV was 0.4, and $T_a$ was $26.7 \degree C$. This suggests that the elderly preferred more air movement when the $T_a$ increased, and an almost “no air movement” sensation in a neutral environment.

At $26 \degree C$ (T), $28 \degree C$ (H), $29 \degree C$ (T), $32 \degree C$ (H), and $33 \degree C$ (T), the proportion of participants who accepted the air movement (AAV $>$ 0) was 85%, 81%, 75%, 50%, and 52%, respectively. With the same criteria as thermal acceptance, the upper limit of the acceptable $T_a$ was approximately $28 \degree C$.

3.1.2. Local weighting factor of thermal sensation

PAC and linear regression were used to determine the weighting factors of the body segments. The extracted factors from PCA could explain more than 85% of the original variance, and the $R^2$ of linear regression was approximately 0.7 for each condition. The weighting
factors of each segment after standardization, and the local thermal sensation and weighting factors are shown in Table 6 and Fig. 6, respectively.

At 26 °C (T), the thermal sensation of each part was negative but still in the neutral range (−0.5 = TSV ≤ 0.5). At 28 °C (H) and 29 °C (T), the thermal sensation of most body parts began to feel "slightly warm". At 33 °C (T), the thermal sensation of each part rose to "warm". At 32 °C (H), the thermal sensation of each part rose to "hot". Additionally, the thermal sensation of the extremities and limbs (calf, forearm, thigh, foot, and palm) was lower than that of the trunk (pelvis, lower back, forehead, chest, and upper back).

At 26 °C (T), the weighting factors of the calf, thigh, and chest were larger. As T1 increased, the weighting factors of the body parts above the red line in Fig. 6, including the extremities and limbs (calf, thigh, forearm, palm, and foot) decreased gradually, whereas those of the body parts below the red line increased gradually. At 28 °C (H) and 29 °C (T), the sum of the weighting factors of the body segments above and below the red line was 0.45 and 0.55, respectively. At 32 °C (H) and 33 °C (T), the sum of the weighting factors of the body segments above and below the red line was approximately 0.35 and 0.65, respectively. As the T0 increased, the local thermal sensation in the torso area had a greater impact on the overall thermal sensation.

3.2. Behavior and psychological changes in local cooling phases

Each device in each condition had a 40-min local cooling phase, and the first 5 min of each local cooling phase were used to measure physiological parameters (Fig. 3). Therefore, data from this time period were not included in the analysis. Analyses started from the 5th min and ended at the 40th min, where the data for the 5th min (T5) were derived from the steady phase before the local cooling phase. Since questionnaires were completed at the 20th (T20, short questionnaire), 30th (T30, short questionnaire), and 40th (T40, long questionnaire) min of each local cooling phase, the whole process was also divided into three parts for the following analyses: the 5–20 min period (T5–T20), 20–30 min period (T20–T30), and 30–40 min period (T30–T40).

3.2.1. Dynamic changes

The device use rate (RU) and proportion of device adjustments (PA) in different time periods were used to describe behavior. The formulas for calculating RU and PA are:

$$R_U = \frac{U_{15-T_1}}{U_{total}}$$ (1)

$$P_A = \frac{A_{T_1-T_2}}{A_{total}}$$ (2)

RU: Use rate of the device in a period,

$U_{15-T_1}$: Number of participants who use the device at time $T_1 - T_2$,

$U_{total}$: Total number of participants in a specific test condition,

PA: Proportion of device adjustments in a period,

$A_{T_1-T_2}$: Number of times the device was adjusted during $T_1 - T_2$,

$A_{total}$: Total number of adjustments in the specific test conditions,

$T_1 - T_2$: Different time periods in a test, including T0–T15, T15–T25, and T25–T35.

Repeated measure ANOVA was used to explore the psychological dynamic change of TSV and ASV among data from T5, T20, T30, and T40. Results are shown in Fig. 7 with the pink shaded regions representing the average RU value of three time periods, and the gray columns representing PA in three time periods.

Significant differences (p < 0.01) in TSV and ASV were observed only between T5 and T20, whereas when using the evaporative cooling device at 32 °C (H), significant differences in TSV were observed between T20 and T30 (p < 0.05). This demonstrates that thermal and air movement sensation varied markedly within the first 15 min and subsequently stabilized.

RU changed the most between T5 and T20 for the three devices under each condition, remained similar for T20–T30 and T30–T40, and changed greatly in the first 15 min and remained nearly unchanged thereafter. PA of the three devices decreased with time. PA for T0–T15, T15–T25, and T25–T35 was approximately 50%, 40%, and 10%, respectively. Most of the adjustments made by the elderly occurred within the first 25 min, after which almost no adjustments were made.

3.2.2. Device-usage model

The elderly’s psychology and behavior stabilized after 25 min. Therefore, the data at T40 were chosen for further analysis. RU increased with increasing air temperature for the three devices (Fig. 7). RU was the lowest at 26 °C (T) and was 11%, 30%, and 32% for the table fan, evaporative cooling device, and air-cooled jacket, respectively. RU was approximately 100% at 32 °C (H) and 33 °C (T) for all devices. The table fan had two speeds: F50% and F100%. The evaporative cooling device had 10 speeds, E100% to E100%, at 10% intervals. The jacket had four speeds, J25% to J100%, at 25% intervals. F50%, E10–50%, and J25–50% were the lower modes (LM); and F100%, E50–100%, and J75–100% were the higher modes (HM). Ordinal regression analysis was used to investigate the relationship between RU and TA (Fig. 8 and Table 7).

Device usage model:

$$R_{(HM)} = \frac{1}{1 + \exp^{-[\alpha + \beta TA]}}$$ (3)
Where $R$ is the use rate of the different modes, $\alpha$ is the constant of the ordinal regression equation, $\beta$ is the regression coefficient, ($\alpha, \beta$ are listed in Table 7.), and $T_a$ is the room air temperature ($^\circ$C).

Fig. 8 illustrates the usage model of all three devices and the average usage of all local cooling devices. As we expected, $R_U$ increased with the $T_a$, whereas $R_H$ had no significant ($p > 0.05$) effect on $R_U$. $R_U$ was 50% at $26.8 \, ^\circ$C. As $T_a$ increased, the use of LM increased initially and
9

subsequently decreased, whereas the use of HM increased. When \( T_a \) was at 28.7 \(^\circ\)C, the use rate of LM was at its highest at 55%. When \( T_a > 30.4 \) \(^\circ\)C, the use rate of HM was greater than that of LM. The \( R_0 \) values of the different devices varied slightly. For the table fan, evaporative cooling device, and air-cooled jacket, the \( T_e \) corresponding to \( R_0 = 50\% \) was 28.0 \(^\circ\)C, 25.7 \(^\circ\)C, and 26.5 \(^\circ\)C, respectively. The \( T_e \) corresponding to the highest LM use rate was 29.3 \(^\circ\)C, 28.4 \(^\circ\)C, and 28.4 \(^\circ\)C, respectively. The \( T_e \) corresponding to when the use rate of HM became greater than that of LM was 30.1 \(^\circ\)C, 31.0 \(^\circ\)C, and 30.0 \(^\circ\)C, respectively.

Generally, despite differences between devices, when \( T_a \) was higher than the preferred temperature and reached 27 \(^\circ\)C, the \( R_0 \) was approximately 50%, and LM was mainly used. When \( T_a \) was close to the upper limit at 28 \(^\circ\)C, the LM use rate was highest at approximately 60%. As \( T_a \) increased to 30.5 \(^\circ\)C, the HM use rate eventually surpassed LM.

### 3.2.3. Change of thermal perception

We further compared thermal perceptions (thermal comfort, sensation, preference, and acceptance) before and after the use of local cooling devices. The data from T5 and T40 were selected, and a paired \( t \)-test was performed for the TSV and TCV. The results of TSV and TCV, and proportion of TAV in different ranges are displayed in Fig. 9.

After using the table fan, under 28 \(^\circ\)C (H), 29 \(^\circ\)C (T), 32 \(^\circ\)C (H), and 33 \(^\circ\)C (T), TCV was 0.3, 0.2, 1.4, and 0.8, and TSV was 0.1, 0.5, 1.4, and 1, respectively. The TCV and TSV were significantly reduced (\( p < 0.01 \)) under all conditions. Using the air-cooled jacket at approximately 29 \(^\circ\)C decreased the thermal sensation from “slightly warm” to the neutral range, whereas using it at approximately 33 \(^\circ\)C reduced the thermal sensation from “warm” to “slightly warm”. At 28 \(^\circ\)C (H), 29 \(^\circ\)C (T), 32 \(^\circ\)C (H), and 33 \(^\circ\)C (T), TSV was 2.1, 2.2, 1.8, and 0; and TSV was 0.2, 0.1, 1.5, and 1.4; and the thermal acceptance (TAV > 0) rates were 50%, 65%, 70%, and 85%, respectively. Therefore, the evaporative cooling device had the ability to alleviate thermal discomfort in environments with a high \( T_a \) of approximately 33 \(^\circ\)C and performed better in environments with low RH.

After using the air-cooled jacket, under 28 \(^\circ\)C (H), 29 \(^\circ\)C (T), 32 \(^\circ\)C (H), and 33 \(^\circ\)C (T), TSV was 0.3, 0.2, 1.4, and 0.8; and TSV was 0.1, 0.5, 1.4, and 1, respectively. The TCV and TSV were significantly reduced (\( p < 0.01 \)) under all conditions. Using the air-cooled jacket at approximately 29 \(^\circ\)C decreased the thermal sensation from “slightly warm” to the neutral range, whereas using it at approximately 33 \(^\circ\)C decreased the thermal sensation from “warm” to “slightly warm”. At 28 \(^\circ\)C (H), 29 \(^\circ\)C (T), 32 \(^\circ\)C (H), and 33 \(^\circ\)C (T), TSV was 2.1, 2.2, 1.8, and 0; and TSV was 0.2, 0.1, 1.5, and 1.4; and the thermal acceptance (TAV > 0) rates were 50%, 65%, 70%, and 85%, respectively. Therefore, the evaporative cooling device had the ability to alleviate thermal discomfort in environments with a high \( T_a \) of approximately 33 \(^\circ\)C and performed better in environments with low RH.

### 3.2.4. Change of air movement perception

Air velocity, air velocity fluctuations, air temperature, overall thermal sensation, and activity level influence the perception of air movement. This study did not discuss the specific effects of these factors but instead a direct questionnaire was used to assess the participants’ perception of the current air movement. Data from T5 and T40 were selected, and a paired \( t \)-test was performed for ASV. The results of ASV, and proportion of AAV in different ranges are shown in Fig. 10.

As shown in Fig. 10 (a), after using the three local cooling devices under all conditions except 26 \(^\circ\)C (T), ASV increased significantly (\( p < 0.01 \)) to approximately 1.0. The air movement acceptance (AAV > 0) rate (Fig. 10 (b)) decreased in most conditions after using the table fan and air-cooled jacket, and increased after using the evaporative cooling device. Air movement acceptance rates at 28 \(^\circ\)C (H), 29 \(^\circ\)C (T), 32 \(^\circ\)C (H), and 33 \(^\circ\)C (T), after using the table fan were 65%, 67%, 35% and 55%; after using the evaporative cooling device 73%, 71%, 65%, and 65%; and after using the air-cooled jacket 62%, 58%, 30%, and 65%.
Fig. 9. Thermal perception vote distribution: (a) TCV; (b) TSC; (c) TPV; (d) TAV (the left side of each condition is the steady phase, and the right side is the local cooling phase of the corresponding device).

Fig. 10. Air movement perception vote distribution: (a) ASV; (b) AAV (the left side of each condition is the steady phase, and the right side is the local cooling phase of the corresponding device).
respectively. Considering the acceptance rate of 80%, the “acceptable” criterion was not met under any conditions after using all three devices.

3.2.5. Other effects of air movement

In this section, the remaining air movement-related votes in the questionnaires, including air movement disturbance vote (ADV), air movement preference vote (APV), and the presence of sick building syndrome (SBS), are analyzed. These results may be the reason for the earlier-mentioned “low airflow acceptance rate.” Thus, these results, along with other possible causes, are displayed in a discussion format in this section.

3.2.5.1. Draught. Draught is defined as the unwanted local cooling of the body caused by air movement. In this study, 80% of the elderly accept a state of almost “no air movement” in a neutral thermal sensation in steady phases. However, TSV in local cooling phases was reduced to the range of neutral thermal sensation at 28 °C (H) and 29 °C (T), whereas ASV was nearly 1, indicating “slight air movement.” A previous study found that draught is more likely to occur during neutral and lower thermal sensations [62]. Furthermore, the neck is one of the body parts most sensitive to draught [63]. In this study, the table fan and evaporative cooling device were adjusted to primarily target the torso (although the airflow would still affect the head and neck), whereas the airflow from the air-cooled jacket would flow directly from the collar, with higher air velocity around the neck. Therefore, higher air movement after using the devices at 28 °C (H) and 29 °C (T) may have led to a lower air movement acceptance rate.

3.2.5.2. Affected activities. TSV was reduced to “slightly warm” or “warm” at 32 °C (H) and 33 °C (T). As “draught” was mostly produced under neutral and lower thermal sensations, draught may not be the main reason in these conditions. We examined the usage modes of the devices and discovered that the maximum power mode was not utilized most often, indicating that the elderly did not further increase their air velocity to counteract thermal discomfort. To explore the possible causes, this study used the air movement disturbance vote (ADV; 0 = not disturbed at all, 1 = disturbed, 2 = strongly disturbed) data came from the question “Is the current air movement disturbing?” The primary concern here was whether the elderly’s current activities (reading, Internet browsing, knitting, etc.) are disrupted. Fig. 11 depicts the linear regression results of the ASV and ADV.

The ASV reached a maximum of 1.2 during local cooling phases. Thus, ASV = 1.2 was regarded as the upper limit. When ASV = 1.2, ADV was 0.7, indicating that the participants felt that the air movement was disturbing them. Given that higher modes were used at 32 °C (H) and 33 °C (T), “current behavior is disturbed” can be considered one of the causes of the low air movement acceptance at 32 °C (H) and 33 °C (T).

3.2.5.3. Physical discomforts. The proportion of symptomatic participants before and after using the different devices is shown in Fig. 12.

The number of people who experienced discomfort after using the device increased. At 28 °C (H), 29 °C (T), 32 °C (H), and 33 °C (T), the proportion of symptomatic participants before using the devices was 15%, 17%, 4%, and 20%; and after using the devices it was approximately 35%, 25%, 25%, and 40%, respectively. Therefore, this may also be one of the reasons for the low air movement acceptance.

3.2.5.4. Individual differences. Fig. 13 (b) shows that the mean value of APV fluctuated slightly in the range of −0.3 to 0.1. In most conditions, the distribution of APV was different from that of TPV after using the three devices as depicted by the violin plots in Fig. 13. TPV (Fig. 13 (a)) was mainly distributed below the 0 scale, and the proportion increased with increase in temperature, whereas APV was symmetrically distributed around the 0 scale, indicating that APV was polarized. This indicates that air movement preferences varied among the elderly. These differences may originate from individual differences among the elderly, such as sex, frailty, education, economic status, and other factors.

Based on these findings, the following observations could be made: When alleviating thermal discomfort by increasing the ambient airflow, airflow cannot be increased indefinitely. When the thermal sensation is reduced to the neutral range, the airflow must be as low as possible to prevent draught. Even if the participants preferred a lower thermal sensation, they did not increase their airflow further as the temperature increased. Physiological discomfort, such as headaches and eyes, nose, and throat irritation could arise from higher airflow, and their current activities might also require appropriate airflow. When these nuisances occur, elderly people compromise between thermal sensation and air movement acceptance. In addition, there are differences among elderly individuals, and individual air movement preferences were not as consistent as thermal preferences or even more significant than the difference between thermal preferences.

4. Discussion

4.1. Thermal sensitivity and effects of local thermal sensations

If the coefficient of $T_g$ in the linear regression was considered a “thermal sensitivity” index, then it would be 0.324 in this study. Table 8 shows the thermal sensitivities of the elderly [21,24] and young adults [64,65] obtained from other studies. Although the local climate where participants live has an effect on thermal sensitivity [27], the elderly are consistently less sensitive than the young [24–26]. Low thermal sensitivity indicates that elderly individuals are insensitive to changes in the
ambient $T_a$.

Furthermore, the lower extremities have little effect on the overall thermal sensation, and the overall thermal sensation is similar to that of the upper body [60]. This is because the lower body is further from the core. The head was considered to have a greater influence on overall thermal sensation owing to its dense capillaries and blood supply, which account for 14% of cardiac output. The results of the present study are consistent with these conclusions, with smaller weight coefficients for the lower body (thigh, calf, and foot) than the trunk and head. However, this is consistent with these conclusions, with smaller weight coefficients for the lower body (thigh, calf, and foot) than the trunk and head. According to the fan-use model obtained by He et al. [42] after analyzing 54 studies, usage exceeded 50% when the indoor $T_a$ reached 28.5 °C, a temperature a little higher than the upper-limit of temperature for 80% thermal acceptability. However, the occupants’ thermal unacceptability did not necessarily lead immediately to air conditioner switch-on. By comparison, the relationship between device usage and indoor $T_a$ determined in other studies is depicted in Fig. 14. Wu et al. [57] discovered in a nursing home that fan usage of the elderly increased dramatically when indoor $T_a$ exceeded 29 °C. According to the fan-use model obtained by He et al. [42] after analyzing 54 studies, usage exceeded 50% when the indoor $T_a$ was 28.9 °C. The 50% utilization rate $T_a$ in these studies were higher than the threshold $T_a$ of 28.5 °C.

This study’s upper limit of 80% acceptable temperature was 28 °C, hence this threshold (28.5 °C) was also deemed appropriate for this study. In contrast, the 50% utilization rate $T_a$ for three local cooling devices in this study was lower than 28.5 °C. On the one hand, it reflected that the elderly actively interacts with devices to maintain thermal comfort before thermal unacceptable. On the other hand, considering that this experiment only provided local cooling devices, the temperature difference of about 2 °C may indicate the benefits of other thermal adaptations, such as opening windows, reducing clothing, drinking water, etc., as well as thermal histories, etc. However, research [25] suggests operating windows is unlikely for the elderly unless it is

### Table 8

Comparison of thermal sensitivity and thermal acceptance upper limit with other studies.

<table>
<thead>
<tr>
<th>Area</th>
<th>Group</th>
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<th>Thermal acceptance upper limit</th>
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<td>28.0 °C</td>
<td>This study</td>
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<td>–</td>
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4.2. Thermal acceptance and behavioral responses of elderly people

Here, the upper limit of acceptable $T_a$ for the elderly was 28 °C. Under 50% RH, the $T_a$ corresponding to the lower and upper limits of the neutral thermal sensation (−0.5 < TSV < 0.5) was 24.5 °C and 27.6 °C, respectively. Therefore, when thermal sensation exceeds the neutral (TSV = 0.5), the thermal acceptance rate of the elderly will be less than 80%. This means that elderly people may have a narrow acceptable $T_a$ range. The acceptable $T_a$ for the elderly [69–71] and young [7,71,72] evaluated by other studies are presented in Table 8, and the acceptable $T_a$ for the elderly is lower than that for the young. The neutral zone for the elderly is consistent with the present design criteria, as was shown. However, the Ministry of the Environment and Ministry of Social Affairs and Health of Finland provided that the upper limit for the indoor air temperature in occupied apartments is 32 °C [73], which may be high for the elderly.

It is possible that with low thermal sensitivity and a narrow thermal acceptance range, the elderly may experience rapid thermal unacceptability when their heat stress exceeds a certain threshold, which motivates them to use cooling devices. Jian et al. [56] confirms this hypothesis. They explored the relationship between air conditioner switch-on and elderly occupants’ thermal tolerance and found that thermal unacceptability increased dramatically when indoor $T_a$ reached 28.5 °C, a temperature a little higher than the upper-limit of temperature for 80% thermal acceptability. However, the occupants’ thermal unacceptability did not necessarily lead immediately to air conditioner switch-on. By comparison, the relationship between device usage and indoor $T_a$ determined in other studies is depicted in Fig. 14. Wu et al. [57] discovered in a nursing home that fan usage of the elderly increased dramatically when indoor $T_a$ exceeded 29 °C. According to the fan-use model obtained by He et al. [42] after analyzing 54 studies, usage exceeded 50% when the indoor $T_a$ was 28.9 °C. The 50% utilization rate $T_a$ in these studies were higher than the threshold $T_a$ of 28.5 °C.

Fig. 13. Distribution of (a) TPV and (b) APV before and after using devices.

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easy for them. Also, the normal summer clothing insulation of 0.5 clo was used in this study. Although the further reduction is available, it is quite limited. Therefore, these simple-to-control local cooling devices may be a better choice for the elderly. Moreover, this study discovered that thermal acceptance was slightly lower than 80% after using the local cooling devices at 33 °C (40%). In conjunction with the findings from Jian [56] and Wu [57], the T_a for the elderly begins to use air conditioners was around 32.5 °C (Fig. 14), indicating that the local cooling devices in this study had a large potential to assist the elderly in maintaining thermal comfort during the transition phase from warm to hot environments.

4.3. Limitation

This study used a climate chamber to simulate warm conditions, focusing on the behavioral and psychological changes of the elderly by using three local cooling devices. However, considering the risk of disease and long-term medication, all the elderly recruited for this experiment were healthy; that is, their frailty was not considered. Moreover, the climate chamber’s environment parameters were constant, whereas real environment parameters are always variable, and people may have more adaptive methods. Thus, the device-use models given in this study may not accurately and need further field studies to validate. In addition, the weighting factors of local body parts were obtained in steady state without local cooling; thus, further validation needs to be done in locally cooled or heated conditions. Although this study aimed to provide a reference for the indoor environment design of local residential and nursing homes for the elderly, as well as recommendations for the selection and control of local cooling devices for the elderly during the summer, the above contents could be considered limitations, and need more research in the future.

5. Conclusion

Herein, the following conclusions can be made regarding the thermal responses of the elderly with and without local cooling devices under different warm conditions.

- The neutral temperature of the elderly from northern Europe was 26 °C, their preferred temperature was 26.5 °C and the upper limit of the acceptable temperature was 28 °C. The lowest thermal acceptance rate was observed in environments with high temperature and relative humidity.

- Under neutral conditions, the limbs and extremities of elderly people had lower thermal sensation and greater weightings, resulting in a lower overall thermal sensation. When the temperature was higher, the trunk and head had higher thermal sensations and greater weightings, thereby resulting in a high overall thermal sensation.

- A model of the elderly’s device usage was developed. 50% of elderly people used a local cooling device at 27 °C, and at 29 °C, the use of lower modes of devices was higher at 60%. When the room air temperature was above 31 °C, the elderly were more likely to use higher modes.

- At 28 °C (60%) and 29 °C (40%), the use of a table fan, evaporative cooling device, or air-cooled jacket could reduce the elderly’s thermal sensation to neutral and make more than 80% of people accept the thermal condition.

- At 33 °C (40%) and 32 °C (50%), the use of an evaporative cooling device or air-cooled jacket reduced thermal sensation significantly, but not to a neutral state. Although thermal acceptance rates increased after using all devices, they were less than 80%, except at 33 °C (40%), when evaporative cooling was used. Furthermore, all three devices performed better under conditions of lower relative humidity.

- After using all experimental local cooling devices, the acceptance rate of air movement declined. The elderly liked air movement that “exists but unnoticeable” when their thermal sensation was neutral. When the air movement was higher, it disturbed the elderly and caused physical discomfort. In addition, there were more individual differences in air movement preference than in thermal preference.

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CRediT authorship contribution statement

Minzhou Chen: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. Azin Velashjerdi Farahani: Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. Simo Kilpeläinen: Writing – review & editing, Supervision, Software, Methodology, Investigation. Risto Kosonen: Writing – review & editing, Supervision, Project administration, Conceptualization. Jaafar Younes: Writing – review & evaluation, Validation. Nesreen Ghaddar: Writing – review & editing, Supervision, Conceptualization. Kamel Ghali: Writing – review & editing, Supervision, Conceptualization. Arsen Krikor Melikov: Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Risto Kosonen reports financial support was provided by Academy of Finland. Minzhou Chen reports financial support was provided by China Scholarship Council.

Data availability

The authors do not have permission to share data.

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