A thermal comfort environmental chamber study of older and younger people

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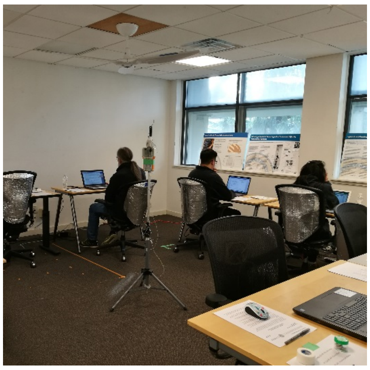
ABSTRACT

We investigated whether or not, when exposed to the same conditions, older people (those aged 65 and over) had different thermal sensations, comfort, acceptability and preferences from their younger counterparts. The study was conducted in a thermal comfort environmental chamber, involving 22 older (average 69.7 years old) and 20 younger (29.6 years old) subjects, exposed to four test conditions between slightly cool and slightly warm. Subjective thermal comfort perceptions for local body parts and whole-body were surveyed. Skin temperatures were measured at four body locations: neck, right scapula, left hand, and right shin. We also investigated the correlation between the frailty level of the subjects and their thermal comfort levels. The study found no significant difference between the thermal sensation, comfort and acceptability of older and younger subjects. We also found no correlation between subjects' frailty level and their thermal sensation, comfort, acceptability and preference but we did not have many frail subjects. In both older and younger subjects, the hand's skin temperature had a significant correlation with the local and overall thermal sensation.

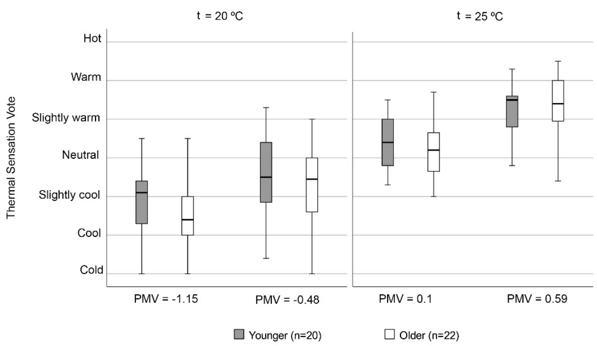
Key words: thermal comfort, environmental chamber study, older and younger people

GRAPHICAL ABSTRACT

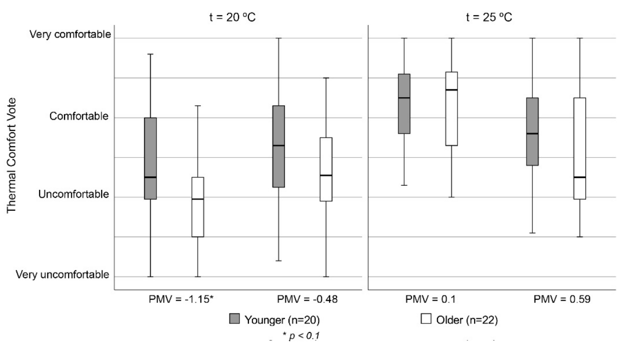
A. Environmental chamber for the study:



B. Thermal sensation:



C. Thermal comfort:



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1. Introduction

The proportion of older people in society is increasing rapidly. Worldwide, the numbers of those aged 60 years or over today are more than twice the numbers in 1980 [1]. However, despite the fact that now most people can expect to live longer than 60 years old, many do not live in healthy conditions [2]. Improving the living conditions of older people requires an understanding of their needs and preference about mobility, safety and comfort, including thermal comfort.

As people age, their ability to detect changes in their thermal environment, such as to detect cold and warm conditions, decreases, and their thermal comfort perception tends to differ from that of younger adults [3]. This condition is connected to the facts that as people age, they experience reduced muscle strength hence reduced work capacity, which resulting in lower metabolic rate [4], reduced muscle volume and increased fat percentage [5], decreased thermoregulatory response [6], decreased heat tolerance [7] and lower cardiovascular flexibility [8].

Although a number of studies have found differences in thermal comfort of older people compared to their younger counterparts, the results are not consistent. As a result, buildings particularly housing, continue to be designed to meet standards that were developed based on studies of younger populations. Both ASHRAE Standard 55 [9] and CEN Standard EN15251 [10] are based on studies of younger adults and they assume that similar conditions are also valid for older people. This may pose a challenge as the majority of older people prefer to age in place [11], or live independently for as long as possible. However, a house designed with younger occupants in mind may not be suitable to meet the thermal comfort requirements of the same occupants in years to come as they become older.

There are two main consequences of not providing older people with living environments that meet their thermal comfort requirements and preferences. First, living environments that are too cold or too hot can have impacts on the occupants' health. Long exposure to cold conditions may lead to a loss of body heat and a drop in core body temperature, resulting in hypothermia which may then lead to confusion, lethargy, loss of consciousness, and even death. Mortality among older people due to cardiovascular disease tends to increase during cold weather [12]. A long exposure to hot conditions may also result in heart failure, heat-related illness, such as heat stroke, heat exhaustion, dizziness, collapse and death [13]. Exposure to high temperatures may also trigger older people with dementia to be more agitated [14]. As older people are less sensitive to cold and heat exposure, it may take longer for them to respond and make changes to either themselves or to their living environment. In other words, although the thermal environment may pose a danger to their health or well-being, older people may not realize it before it is too late to respond.

The second consequence is the impact on older people's living costs. If a house is poorly designed and is too cold or too hot unless a heater or air-conditioner is used, then paying for the bills to run the heater or air-conditioner can have significant implications for the occupants' living costs [15]. As older people tend to have reduced fixed incomes, constant reliance on heating and cooling to feel thermally comfortable at home can become a financial burden [16].

In this study we investigated whether or not, when exposed to the same condition, older people had a different thermal sensation, comfort, acceptability and preference from their younger counterparts. It is expected that the study will contribute to a further understanding of the thermal comfort of older people.

1.1. Background

More than 80% of thermal comfort studies to date have been conducted with subjects aged between 20 and 25 years old [17]. For the studies that did involve older subjects, the results are often not consistent, sometimes even controversial.

1.1.1. Lab studies

Studies that found no significant effects of age

Fanger [18] conducted thermal chamber experiments with eight set-point conditions that were kept constant for three hours, involving 128 older (average age of 68 years old ± 4.7) and 128 younger subjects (23.1 years old ± 2.2) with half the subjects being males. The subjects had the same clothing value and did a similar activity to ensure that they had the same metabolic rate. Fanger did not find any significant differences in the thermal sensation between the older and younger subjects and their preferred temperature was the same at 25.7° C. He hypothesized that although the older subjects had lower metabolism, their lower evaporative loss might compensate for this, resulting in the same preferred thermal environments [19].

Later Taylor et al. [20] conducted a thermal comfort study of older and younger males (66.9 years ± 4.1 and 22.9 ± 2.9; mean ± SD, respectively) with similar body mass, height and sum of skinfold thickness, also in a chamber; however, the number of subjects was not reported. The subjects were allowed to adjust the indoor temperature to reach their preferred conditions. The study also found no age-related significant differences in the preferred temperature (24.9 ºC for the younger and 24.5 ºC for the older; $p > 0.05$). The study, however, found that the skin temperatures of the older group were significantly lower than that of the younger group in both heat-induced and cold-induced changes (mean temperature difference of 1 ºC, $p < 0.05$). The term 'heat-induced' refers to the condition when the subjects changed the temperature controller from heating to cooling while 'cold-induced' refers to the change from cooling to heating [20]. The older group was also found to feel colder, less uncomfortable and feel better ($p < 0.05$) in cold-induced changes; however, during heat-induced changes, their thermal sensation was equivalent to that of the younger group but they were also more comfortable and felt better ($p < 0.05$). This result suggests that older people may require a more intense stimulus in order to take appropriate behavioural response to the change in their thermal condition.

Kalmár [21] conducted a study to analyse the relationship between sex and age and thermal sensation in a warm environment, involving 20 young and 20 elderly subjects with 10 females and 10 males in each group. All subjects had a clothing thermal insulation value of 0.5 clo and sedentary activity level. The air and mean radiant temperatures were fixed at 30 ºC and the subjects were exposed to this condition for 2 hours. The study found that the younger females had a significantly lower thermal sensation vote compared to the other groups ($p < 0.05$), 0.48, 0.76 and 0.75 lower than that of the thermal sensation of the older females, younger males and older males, respectively. All groups perceived the condition to be between 'just acceptable' and 'clearly acceptable', with the lowest acceptance value found in the older male group whereas the highest acceptance value found in the older female group. This indicated that age did not result in a significant difference in the thermal acceptability between the two age groups.

Studies that found significant effects of age

The work by Natsume et al. [22] was one of the first studies that found a difference in preferred temperature between older and younger subjects. They studied the effects of age on thermal sensitivity by exposing six older men (73 ± 2) and six younger men (24 ± 4) to 20 and 40 ºC in a chamber during summer and winter. The study found that the older subjects had a wider range of preferred temperature. Their preferred temperature during summer when the test started at 20 ºC was significantly lower than their preferred temperature when the test started at 40 ºC ($p < 0.01$) and was also significantly lower than their preferred temperature when the test started at 20 ºC during winter ($p < 0.05$). On the contrary, no significant difference was found in the preferred temperature of the younger subjects between the two test conditions and two seasons. Natsume et al. [22] argued that as people aged, their thermal sensitivity to cold decreased during summer.

Ten years later, Tsuzuki and Ohfuku [23] compared the thermal sensation and thermoregulation of 109 older (72.4 ± 5.3) and 100 younger (23.5 ± 2.2) subjects in Japan in a chamber with varying set point temperatures: 23, 25, 27, 29 and 31 ºC and with 60% RH. They found that the older subjects' thermal sensations were lower than that of the younger subjects at 31 ºC but higher at 23 ºC though no statistical tests were reported. They suggested that these might be due to the older subjects having reduced thermal sensitivities to warm and cool environments, similar to the suggestion by Natsume et al. [22]. Tsuzuki and Ohfuku also found that the majority of the older subjects reported wanting "no change" at 27 ºC whereas for the younger subjects the preferred temperature was 25 ºC.

Schellen [24] and Schellen et al. [25] compared the physiological and psychological response of 8 younger and 8 older males to a steady-state (21.5 ºC) and a temperature drift condition (2K/h from 17 to 25 ºC). They found that at the same temperature, the older males felt significantly more uncomfortable ($p < 0.001$). The thermal sensation votes (in the 7-point ASHRAE thermal comfort scale) of the older subjects were generally 0.5 scale units lower than that of the younger subjects under the same temperature, indicating a 1 ºC higher of neutral temperature, or that the older subjects preferred warmer conditions.

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1.1.2. Field studies

In recent years more thermal comfort studies of older people have been conducted not in a controlled environment but in their home environment. Unlike lab studies which found inconsistent or controversial results regarding the age effect on thermal sensation, most field studies have shown some differences in thermal comfort between the older and younger subjects.

Thermal sensation

Wong et al. [14] conducted a field study in elderly centers in Hong Kong involving 384 people aged 60 to 97 years. Similar to the study by Schellen et al. [24], they found a decay of one Predicted Mean Vote (PMV) scale for every 25.3 years age increase ($p < 0.05$). This result indicates that people might become less sensitive to warm but more sensitive to cool environments as they age.

On the contrary, in a field study involving 400 subjects aged 50 years or younger and 200 subjects older than 50 years, Peng [26] found that on average, the older people's "thermal comfortable temperature" was slightly lower than their younger counterparts in summer by 0.48 K, and slightly higher in winter by 0.49 ºK, indicating that older people were more sensitive to both warm and cool conditions. It is however not clear whether this "thermal comfortable temperature" means the neutral or preferred temperature.

Neutral temperatures

Older vs. younger. The field study by Hwang and Chen [27] involved 87 subjects in Taiwan aged 60 to 82. They found that the subjects' seasonal neutral temperatures were 25.2 ºC in summer and 23.2 ºC in winter. These neutral temperatures were higher than the neutral temperatures of younger subjects (aged 20 to 60) in a study by Liu et al. [28] which found that the neutral temperatures were 24.3 ºC in summer and 21.1 ºC in winter. The raised neutral temperatures of older people for both summer and winter supports the findings in [14] that older people preferred warmer conditions than their younger counterparts.

Winter vs. summer among older people. A study by Jiao et al. [29] involving 672 older subjects in naturally-ventilated homes found a much lower thermal neutrality in winter (16.6 ºC), which was 2.4 ºC lower than the predicted thermal neutrality temperature (19 ºC with clothing level of 1.83 clo) and much lower than that of the studies by Hwang and Chen (23.2 ºC with clothing level of 0.75 clo) [27]. The neutral temperature in summer was found to be 25.4 ºC, which was only slightly lower than the predicted thermal neutrality temperature (26 ºC with clothing level of 0.48 clo), similar to the neutral temperature of 25.2 ºC (0.61 clo) in [27], and higher than the neutral temperature of 24.3 ºC (0.26 clo) in [28]. Another field study in free-running aged care homes in Shanghai by Wang et al. [30] involved more than 1000 older people. They found very similar neutral temperatures in winter as [29], 16.7 ºC, and 25.1 ºC in summer. The two very similar low thermal neutralities in winter (16.6 and 16.7C) [29, 30] happened in naturally ventilated or the free-running buildings. It seems that older people in those buildings adapted to the cold ambient temperature.

Jiao et al. suggested that lowered neutral temperatures might be due to the decline in thermal sensitivity among the older people [29]. Likewise, Wang et al. suggested that physiological changes experienced by people as they aged influenced their thermoregulation systems, which in turn might have caused changes in their physiological acclimatization and affected their subjective thermal responses [30]. Nevertheless, they warned that low winter neutral temperatures and low thermal sensitivity may pose a threat to their health and suggested that further studies to include measuring the physiological parameters should be conducted in order to judge the health comfort range of older people.

Similar results were also found by Bills [31], who conducted a study of 18 older subjects in their homes in South Australia. The study found that the neutral thermal sensation votes during winter mostly occurred when the indoor operative temperatures were lower than suggested by the ASHRAE 55 but the neutral thermal sensation votes during summer occurred within the 80% acceptability limit of indoor operative temperatures. The study also found that the percentage of time the subjects preferred to be warmer when they voted 'cool' or 'cold' in winter was less than the percentage of time they preferred to be cooler when voted 'warm' or 'hot' in summer, indicating adaptability to lower temperatures as found in [29, 30]. The older subjects also reported experiencing increasing health symptoms, such as coughing, headache and joint pain during colder (and warmer periods) [32]. Bills' analysis shows that least health symptoms occurred between 21 and 24.3 ºC of indoor operative temperatures. In other words, the condition at which the older people felt cool or cold although they preferred no change, i.e. below 21 ºC, might actually pose a health risk without them realizing it.

1.2. Frailty

As people age, the likelihood of experiencing a decline in their health increases. A state of increased vulnerability due to age-related decline is termed ‘frailty’ [33]. Frailty can be understood as “a phenotypical state of weight loss, fatigue, and weakness or alternatively as a multidimensional state of vulnerability arising from a complex interplay of biological, cognitive, and social factors” [34]. The state of frailty that one may experience can be assessed using various tools such as the Frail Scale [35] and the Frailty Index [36]. Assessments of frailty status comprise of a number of domains such as general health status, medication use, cognition, mobility or functional performance, nutrition, mood and social support. It is important to note, however, that, as there are a number of domains relating to health and well-being that determine one’s frailty status, not every ageing person becomes or is considered frail and not everyone considered to be frail has a deteriorating health condition.

One tool to identify the frailty status of a person is the Edmonton Symptom Assessment Scale [37]. The assessment using this tool covers 9 frailty domains: cognition, general health status, functional independence, social support, medication use, nutrition, mood, continence, and functional performance. The response to each of the assessments is used to calculate the Frailty Score.

Thermal comfort studies that have been conducted thus far normally only involve subjects who are considered healthy, often young people. While it is understandable that only involving healthy subjects will ensure that the results are not affected by health-related symptoms, this paper argues that as the proportion of older people in our society keeps increasing, the likelihood of having frail older people, no matter how mild it is, is also increasing. Thus it is timely for thermal comfort studies involving older subjects to consider investigating the relationships between one’s frailty level and thermal sensation, comfort, acceptability and preference. When older subjects were found to be less sensitive to the thermal environment particularly during summer (for example [20, 21]), or that the preferred temperature by the older subjects was higher than the younger subjects [27], or lower [29, 30, 29, 31], it is reasonable to ask the question whether the differences between the older and younger subjects were confounded by their frailty level.

1.3. The study

Our main objective was to investigate whether there were differences in, and which factors were contributing to, the thermal sensation, comfort, acceptability and preference between the older (age 65 years or over) and younger subjects (age less than 65 years). Another question to be investigated was whether the subjects’ thermal sensation, comfort, acceptability and preference correlated with their frailty level (from not frail to severely frail).

The study was conducted in December-January in a controlled environmental chamber at the Center for the Built Environment, University of California, Berkeley.

2. Methods

2.1. Subjects

After receiving an approval from the UC Berkeley’s Committee for Protection of Human Subjects (IRB2010-04-1312), the older subjects were recruited from local organisations, such as senior centres, church, and professor emeritus mailing lists, while the younger subjects were recruited mainly from the student body at the University. People who responded to the invitation to participate were asked to fill out an online background survey which asked questions such as their age, sex, body weight and height. A total of 28 older and 42 younger people responded to the invitation, and from these 24 older and 24 younger people were recruited based on their availability during the weeks the tests were to be conducted. Those in the younger group who indicated that they were smokers or regularly taking medications were also excluded. Note, however, that 2 older and 4 younger subjects had withdrawn before the tests started due to conflicting schedules, thus the final numbers of subjects are 22 and 20, older and younger, respectively. The age of the older subjects ranged from 65 to 84 years with the majority (13 subjects) aged between 65 and 70, 5 aged between 71 and 75, 3 aged between 76 and 80, and one aged 84 years old. The age of the younger subjects ranged from 19 to 54 years old with the majority (13 participants) being younger than 30 years old, 5 subjects between 31 and 40, and 2 subjects older than 40 years old. Subjects' details are presented in Table 1.

Each subject was supposed to participate in two test conditions: 20 and 25 ºC, held at least one week apart; however, 2 older subjects and 3 younger subjects were not able to participate in the second test due to illness and other personal matters unrelated to the test.

Table 1. Study subjects

	Older		Younger	
	Male (n=9)	Female (n=13)	Male (n=8)	Female (n=12)
Age (years)	68.8 (3.7) [65-75]*	70.4 (5.9) [65-84]	28.0 (11.2) [19-54]	30.7 (8.3) [21-49]
Weight (kg)	80.8 (12.9) [65.8-102.1]	65 (19.3) [43.5-118.8]	76.7 (10.3) [59.0-91.6]	62.4 (18.5) [47.6-108.8]
Height (cm)	175.6 (9.2) [163-188]	159.4 (7.4) [147-172]	170.0 (10.0) [165-183]	160.0 (0.0) [155-167]

* Results are reported as arithmetic mean (standard deviation) [minimum value – maximum value]

2.2. *Experimental setup*

The environmental chamber was a 5.4 × 5.4 × 2.65 m (length × width × height) room with two external walls with windows facing south and west. The outside horizontal overhangs and vertical fins shield the chamber from direct solar radiation. Two desks and chairs were arranged along each of the three sides of the room so that the subjects faced the wall/window instead of facing each other (see Figure 1 for the chamber setup). The window temperatures were thermally controlled by the air temperature going through a gap between the inner (single-pane) and outer (double-pane) glazing of the windows, so the room air and mean radiant temperatures were identical, which were set at 20 ºC for the first test and 25 ºC for the second test. The relative humidity was set at 40% and the air speed was less than 0.1 m/s during both tests. The chamber has the capability to control ambient temperature with +/- 0.5 ºC of the setpoint at a range between 13 – 35 ºC, and relative humidity with +/- 2% [38, 39]. Ventilation rates were maintained at 25 l/s per person or higher. Another set of temperature, humidity and air velocity sensors were placed in the middle of the chamber at 3 heights: 0.1m, 0.6m, and 1.1m, as seen in Figure 1, to ensure that these setpoint conditions were maintained during the tests. The temperature sensors (WZYCH4, Tianjin Huayi) had 0.1 ºC accuracy whereas the relative humidity sensors (HOBO U12-012, Onset) had ± 2.5% accuracy from 10% to 90% RH. Air velocity was measured with a low flow anemometer (Sensor-electronic) with an accuracy of ±0.02m/s (0.05 – 5 m/s).

As the schedule of the tests depended on the availability of the subjects and since the chamber could only fit up to 6 subjects, the tests had to be conducted in 18 sessions: 9 sessions with 20 ºC and another 9 sessions with 25 ºC room set point temperatures.

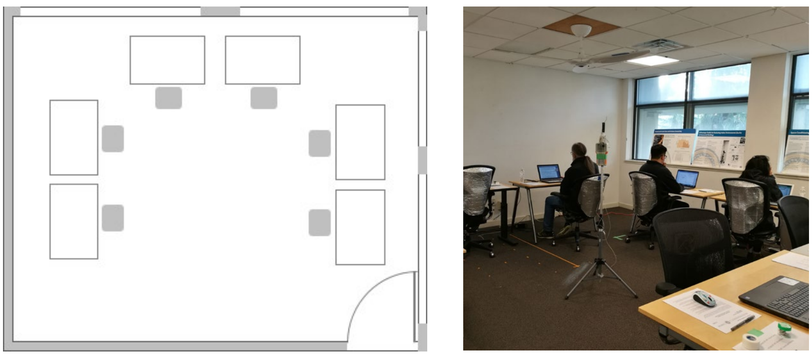

Figure 1. Room layout during the test

2.3. Test conditions and subjects' clothing

We wanted to test conditions covering thermal sensation from slightly cool, neutral, to slightly warm; however, we also wanted to reduce the number of subjects' visits because half of the subjects were older people. It was not possible to change the thermal condition of the chamber in a short time therefore we applied a strategy of using *clothing* to create the planned thermal sensation ranges.

In both tests, all subjects were instructed to wear a pair of long pants, long sleeved thin shirt, underwear, calf height socks and closed shoes. Subjects who came with shirts that appeared to be too thick, or those who came with short sleeved shirts, were asked to change and wear a long sleeved thin shirt provided by us. We then provided each subject with the same type of long sleeve fleece jacket.

The test chamber was set at 20 ºC for the first test and 25 ºC for the second test. For each test condition, a subject changed clothing by adding/taking off the jacket. Without the jacket, the clothing value was estimated to be 0.72 clo, including the chair, while with the jacket, it was 1.06 clo. With the two clothing insulation levels and the two ambient conditions, the four tested conditions corresponded to PMV = -1.15, -0.48, 0.1, and 0.59.

2.4. Training on test procedure and thermal questions

A 40-min preparation session was held inside the chamber prior to the first test. During this session, the subjects were provided with an information sheet detailing the procedure of the test and were asked to sign the consent form. The researcher then provided an explanation on the test procedure and questions to be asked during the test as well as instructions on how to respond to the online survey using either the provided computers or the participant's own laptops. No information session was given prior to the second test as the subjects already knew how to answer the questions.

2.5. Health/well-being and frailty questionnaire

Following the information session and before the test, each participant was asked to respond to a more specific background survey which asked questions relating to their health and well-being. These included questions about health symptoms they may have experienced during the most recent hot and cold weather, as well as questions to investigate the subjects' frailty levels. This study used questions from the validated Edmonton Frail Scale [40].

The questions and their possible scores for the Edmonton Frail Scale are presented in Table 2. Note that as the subjects only responded to the questions using a laptop, the first question had been modified from asking the subjects to draw a clock to indicate a specified time (i.e. ten minutes after eleven), to asking the participant to indicate the specified time, by clicking on the face of a clock on the screen. A modification was also applied to the functional performance domain because it was not possible for the subjects to walk around due to the size of the chamber. In the original version of the Edmonton Frail Scale the subject would be asked to stand up and walk for approximately 3 min, return and sit down, while being timed, to test their functional performance [37]. In this test, this assessment was replaced by three questions as used in Hilmer et al. [41]. See Table 2 below.

A total score of 0 to 5 indicates 'not frail', 6 to 7 'vulnerable', 8 to 9 'mild frailty, 10-11 'moderate frailty' and 12 to 17 'severe frailty. Note that while most subjects only responded to the above questions prior to the first test, a number of subjects had to respond to the Edmonton Frail Scale question again during the acclimatisation period in the second test if the second test was held more than two weeks after the first test. This was because the last question, as shown in Table 2, asked the subjects to reflect on what happened two weeks prior to taking the test.

2.6. Skin temperature measurements

Skin temperature sensors were placed directly on four body locations of each participant using a tape, following the procedure of ISO 9886:2004 [42]: back of the neck, right scapula, left hand, and right shin.

Note that this Standard recommends the 4-points skin temperature measurement for warm and hot conditions; however, we adopted this approach even though our test conditions were slightly cool to neutral, in order to avoid older people feeling uncomfortable from having many sensors on their bodies. The skin temperatures were continuously monitored using small wireless temperature sensors (PyroButton-L, Opulus). The use of such device for skin temperature measurements has been validated [43]. The measured skin temperatures would be used later to calculate the mean skin temperature, using the following equation:

$$t_{sk} = 0.28\ t_{neck} + 0.28\ t_{scapula} + 0.16\ t_{left\ hand} + 0.28\ t_{shin} \qquad (1)$$

2.7. Thermal comfort survey questions

We planned two survey questionnaires, long and short. The long thermal comfort survey (Table 3) includes thermal sensation and comfort for the whole-body, as well as a few selected body parts (head, hands, feet, and legs). It also included questions about the subjects' perceptions and acceptability of the air quality, odour, irritation level on the eyes, nose and throat, and ability to concentrate and do work. However, in this paper, we focus on thermal sensation, comfort, acceptability and preference and how these may have been affected by the subjects' age and frailty level. Therefore, the other questions are not included in Table 3. The short thermal comfort survey only included questions about their whole body thermal sensation, comfort, acceptance and preference. The subjects indicated their response to the question by clicking and sliding the indicator along the respective bar on the online survey form. They could place the indicator at any place along the bar, and not necessarily on the exact round number. Note that while in the question about thermal sensation the subjects can indicate the middle value (0 or 'neutral sensation'), for questions about thermal comfort and acceptability the response must be either greater or less than 0. This was because one cannot be neither comfortable nor uncomfortable or a thermal condition cannot be neither acceptable nor unacceptable.

Table 2. Edmonton Frail Scale used in the study

Frailty domain	Item	0 point	1 point	2 points
Cognition	Please click two black bars to indicate a time of "ten after eleven." First click is to indicate the HOUR. The other click is for MINUTE. You have 20 seconds for the question.	No error	One error either in indicating the hour or the minute	Two errors in indicating both the hour and the minute
General health status	In the past year, how many times have you been admitted to a hospital? In general how do you describe your health?	0 Excellent/very good/ good	1-2 Fair	≥2 Poor
Functional independence	With how many of the following activities do you require help? Meal preparation, shopping, transportation, telephone, housekeeping, laundry, managing money, taking medications	0-1	2-4	5-8
Social support	When you need help, can you count on someone who is willing and able to meet your needs?	Always	Sometimes	Never
Medication use	Do you use five or more different prescription medications on a regular basis? At times, do you forget to take your medications?	No No	Yes Yes	
Nutrition	Have you recently lost weight such that your clothing has become lose?	No	Yes	
Mood	Do you often feel sad or depressed?	No	Yes	
Continence	Do you have a problem with losing control of urine when you don't want to?	No	Yes	
Self -reported	Two weeks ago, were you able to:	No	Yes	

performance	1. Do heavy work around the house like washing windows, walls or floors without help? 2. Walk up and down the stairs without help? 3. Walk 1 km without help	No No	Yes Yes	

Table 3. Thermal comfort survey questionnaire

Questions	**Response options**
Rate your current whole body thermal sensation	-3 (cold), -2, -1, 0 (neutral), 1, 2, 3 (hot)
Rate your whole body thermal comfort (select a non-zero value)	-3 (very uncomfortable) to 3 (very comfortable)
Rate your acceptance of the current thermal environment (select a non-zero value)	-3 (clearly unacceptable) to 3 (clearly acceptable)
Rate your local thermal sensation for your head	3 (cold), -2, -1, 0 (neutral), 1, 2, 3 (hot)
Rate your thermal comfort for your head (select a non-zero value)	-3 (very uncomfortable) to 3 (very comfortable)
Rate your local thermal sensation for your hands	-3 (cold), -2, -1, 0 (neutral), 1, 2, 3 (hot)
Rate your thermal comfort for your hands (select a non-zero value)	-3 (very uncomfortable) to 3 (very comfortable)
Rate your local thermal sensation for your legs	-3 (cold), -2, -1, 0 (neutral), 1, 2, 3 (hot)
Rate your thermal comfort for your legs (select a non-zero value)	-3 (very uncomfortable) to 3 (very comfortable)
Rate your local thermal sensation for your feet	-3 (cold), -2, -1, 0 (neutral), 1, 2, 3 (hot)
Rate your thermal comfort for your feet (select a non-zero value)	-3 (very uncomfortable) to 3 (very comfortable)
You would prefer to be:	-1 (cooler), 0 (no change), 1 (warmer)

2.8. Test procedure

There were three phases in each test as shown in Figure 2: a 30 minute acclimatization period, then two phases each continued for 45 minutes. In the first phase when the ambient temperature was set at 20 °C, the subjects began by wearing an additional jacket, provided by the researcher. The subjects were asked to remain sedentary to allow the body to acclimatize with the indoor condition. During this time the subjects could read a book, browse the internet, read or write emails, occasionally chat with each other, knit, or do homework. The metabolic rate was estimated to be 1.0 Met [9]. After 17 minutes, the subjects were asked to stand up to do a very light exercise or movements for 1 minute, such as stepping up and down a low stool for ten steps or walking on a spot without using the stool, to prevent their metabolic level from declining during the test.. This approach has been applied in previous studies, for example [44, 45]. At the end of the next 17 minutes the subjects were asked to respond to the long thermal comfort survey questionnaire. Following this phase II started. Half of the participants in each group, randomly selected, were asked to take off the jacket, thus the estimated clothing value became 0.72 clo, while the other half continued wearing the jacket. After 5 minutes the subjects were asked to respond to the short thermal comfort survey, and again at the end of the next 5 minutes. Similar to the first phase, at the end of the following 35 minutes the subjects responded to the long survey. Following this was the third phase. Those who had the jackets on were asked to take them off, whereas the rest were asked to wear the jackets.

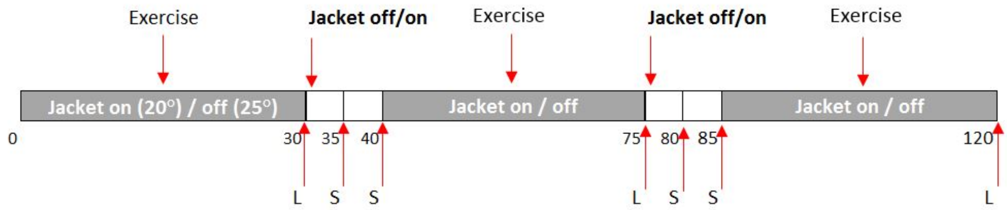

Figure 2. Test procedure

(L = long survey; S = short survey, number under the chart representing time in min)

In the second test when the ambient temperature was set at 25 °C, the subjects began by not wearing the jacket. After responding to the thermal comfort survey, half subjects were asked to wear the jackets whereas the other half continued to not wear the jackets. The procedure was then similar to the first test: answering a short survey after 5 minutes, twice, then answering the long survey after 35 minutes. Those who had the jackets on were then asked to take the jackets off, whereas the rest were asked to wear the jackets. All subjects then answered the short survey, twice, at 5 minute intervals, then answered the long survey after 35 minutes. Similar to the first test, subjects were asked to stand up and do a very light exercise for one minute, at 17 minutes after each session started. In both tests, the survey responses to be analysed were from the second and third phases.

2.9. Data analysis

All surveys were conducted online using Qualtrics [46]. The results were then entered and analysed in the SPSS statistical package [47], to investigate 1) whether age was a significant factor affecting subjects' responses to thermal sensation, comfort, acceptability, preference, 2) whether frailty affected those subjective responses, and 3) other significant factors that affected these subjective thermal responses. Thus in the analyses the dependent variables were: thermal sensation votes (TSV), thermal comfort votes (TCV), thermal acceptability votes (TAV) and thermal preference (TP), while the independent variables were: age, age group (older, younger), sex (female, male), weight and frailty score. The analyses were conducted for all four test conditions or PMV proxies. Correlations between skin temperatures, thermal sensation, comfort, acceptability and preference were also analysed.

3. Results

The results showed that the responses to the short surveys on the whole body thermal sensation, acceptability, comfort and preference were still influenced by the previous condition (i.e. whether or not jackets were worn). The results presented here are therefore based on the long survey questionnaire, when the subjects had been exposed to the condition for 40 minutes.

3.1. Thermal sensation

Data on mean thermal sensation votes (TSV) of all subjects and of each age group, sex, and set point temperatures were first tested to determine whether they were normally distributed, using the Shapiro-Wilk test. The results show that they were all normally distributed ($p > 0.05$).

Overall there was no significant difference ($p = 0.56$) between the mean TSV of the older group (n = 22) and younger groups (n = 20). At the condition representing PMV = -1.15, the mean TSV of the whole group was -1.27 (SD = 0.85), and no statistically significant difference was found between the mean TSV of the older and younger groups, (O = -1.45 (0.86); Y = -1.07 (0.81), $p = 0.14$). There was also no significant difference between the mean TSV of the older and younger females (OF = -1.51 (0.89); YF = -1.29 (0.88), $p = 0.55$), though the difference between the older and younger males was significant at $p = 0.1$ level (OM= -1.37 (0.84); YM = -0.72 (0.60), $p = 0.095$). Within each age group, no significant difference was found between older females and males ($p = 0.71$) and between younger females and males ($p = 0.13$).

At PMV proxy = -0.48, the mean TSV of the whole group was -0.6 (SD = 1.06). No statistically significant difference was found between the older and younger groups, (O = -0.63 (1.07); Y = -0.57 (1.07), $p = 0.86$). TSV of the older females was similar to younger females (OF = -0.58 (1.25); YF = -1.09 (0.99), $p = 0.28$); however, the mean TSV difference between older and younger males was significant (OM = -0.69 (0.82); YM= 0.21 (0.65), $p < 0.05$). The younger males had almost 1 TSV higher compared to the older males. Within each age group, there was no significant difference between the TSV of older females and males ($p = 0.83$); however, TSV of the younger females was different from younger males ($p < 0.005$).

At PMV proxy = 0.1, the mean TSV of the whole group was 0.28 (SD = 0.71) and no statistically significant difference was found between the older and younger groups, (O = 0.22 (0.72); Y = 0.35 (0.71), $p = 0.59$). There was also no significant difference between the older and younger females (OF = 0.30 (0.78); YF = 0.51 (0.78), ($p = 0.54$), and between the older and younger males (OM= 0.08 (0.64); YM = 0.13 (0.61), $p = 0.90$). Within each age group, no significant difference was found between older females and males ($p = 0.55$) and between younger females and males ($p = 0.30$).

At PMV proxy = 0.59, the mean TSV of the whole group was 1.28 (SD = 0.78). No statistically significant difference was found between the older and younger groups, (O = 1.23 (0.89); Y = 1.33 (0.67), $p = 0.70$), and between the older and younger females (OF = 1.30 (0.92); YF = 1.07 (0.64), $p = 0.51$), as well as between older and younger males (OM = 1.38 (0.88); YM= 1.46 (0.68), $p = 0.87$). Within each age group, there was no significant difference between the older females and males ($p = 0.85$) and between younger females and males ($p = 0.25$).

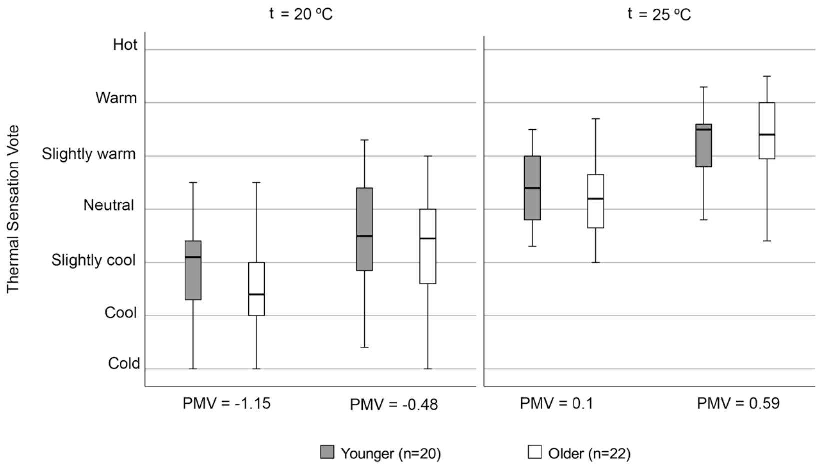

Figure 3. Range of Thermal Sensation Votes between older and younger subjects

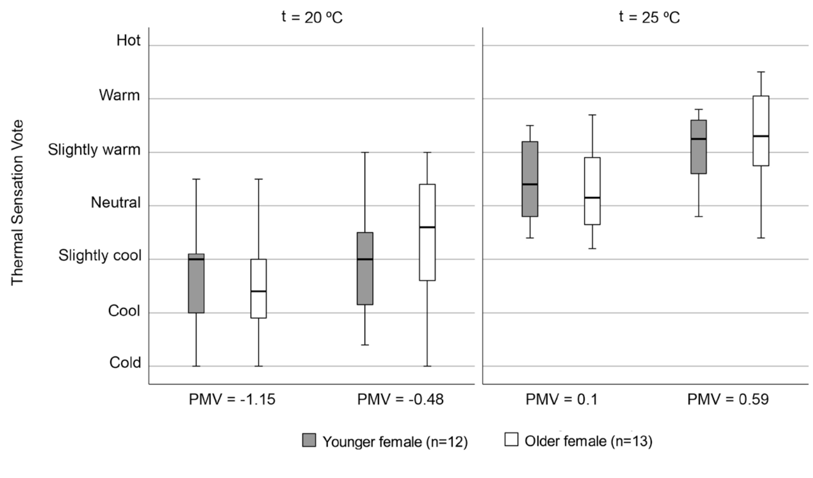

Figure 4. Range of Thermal Sensation Votes between older and younger females

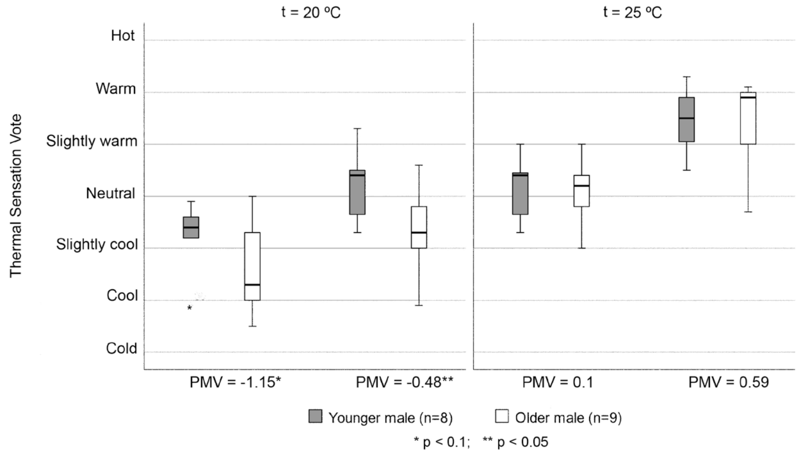

Figure 5. Range of Thermal Sensation Votes between older and younger males

We can conclude that overall, the large majority of tests showed that the thermal sensation for older and younger subjects was the same at both 20 ºC and 25 ºC set points.

The relationships between local and overall thermal sensations were also analysed. The results found that for both groups in most cases the overall thermal sensation significantly correlated with the hand and head thermal sensations. Stronger correlations were found in the older group particularly at lower PMV conditions, as indicated by the Pearson Correlation coefficients (R) shown in Table 4. No significant correlation was found between overall thermal sensation and thermal sensation of the leg in both groups.

Table 4. Correlations between overall and local thermal sensations

PMV	Group	$R_{overall\text{-}hand}$	*p*	$R_{overall\text{-}head}$	*p*	$R_{overall\text{-}feet}$	*p*
-1.15	Older	0.645**	0.001	0.672**	0.001	0.359	0.101
	Younger	0.572**	0.008	0.409	0.073	0.401	0.08
-0.48	Older	0.674**	0.001	0.458*	0.032	0.536*	0.01
	Younger	0.587**	0.007	0.658**	0.002	0.523*	0.018
0.1	Older	0.788**	0.000	0.825**	0.000	0.687**	0.001
	Younger	0.637**	0.008	0.598*	0.014	-0.074	0.785
0.59	Older	0.460*	0.048	0.721**	0.000	0.221	0.364
	Younger	0.553*	0.021	0.593*	0.012	0.373	0.14

** Correlation is significant at 0.01 level
* Correlation is significant at 0.05 level

3.2. Thermal comfort

The Shapiro-Wilk tests for normality showed that data on mean Thermal Comfort Votes (TCV) of all subjects and of each age group, sex, and set point temperatures were normally distributed ($p > 0.05$). Overall, there was a significant difference between the mean TCV of older and younger groups ($p = 0.03$). At PMV proxy = -1.15, the mean TCV of the older subjects was lower than that of the younger subjects (O = -1.00 (1.22); Y = -0.21 (1.54); $p = 0.07$). There was however no significant difference ($p > 0.10$) in the mean TCV between older and younger subjects in the other three PMV proxies.

There was no difference in the TCV between females and males in both age groups; however, within the same sex group, significant difference was found between the TCV of older and younger males at PMV proxy = -1.15 (OM = -0.88 (1.15); YM = 0.59 (1.40); $p < 0.05$), and at PMV proxy = -0.48 (OM = -0.15 (1.33); YM = 0.91 (1.17); $p = 0.10$). TCV of older females at PMV proxy = 0.59 was also significantly different from younger females at $p = 0.1$ level (OF = -0.08 (1.47); YF = 0.86 (1.00), $p = 0.10$). When significant differences were observed, the older subjects tend to vote ‘uncomfortable’ whereas the younger subjects voted ‘comfortable’.

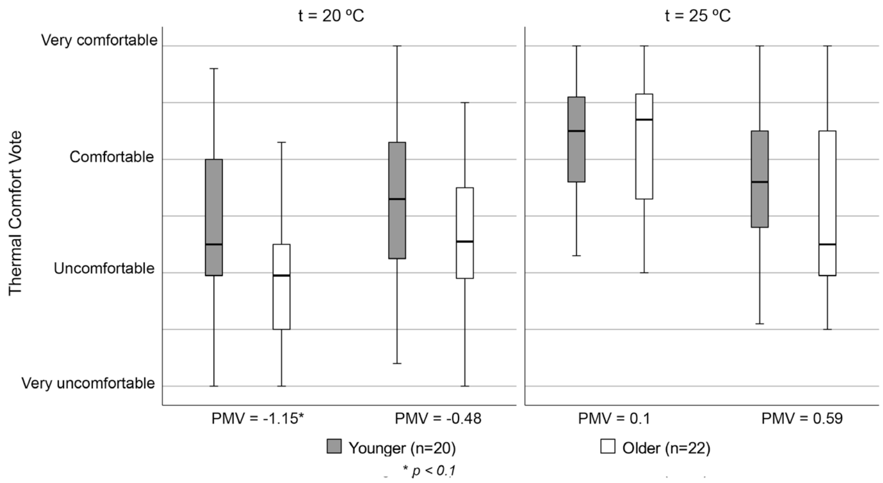

Figure 6. Range of Thermal Comfort Votes between older and younger subjects

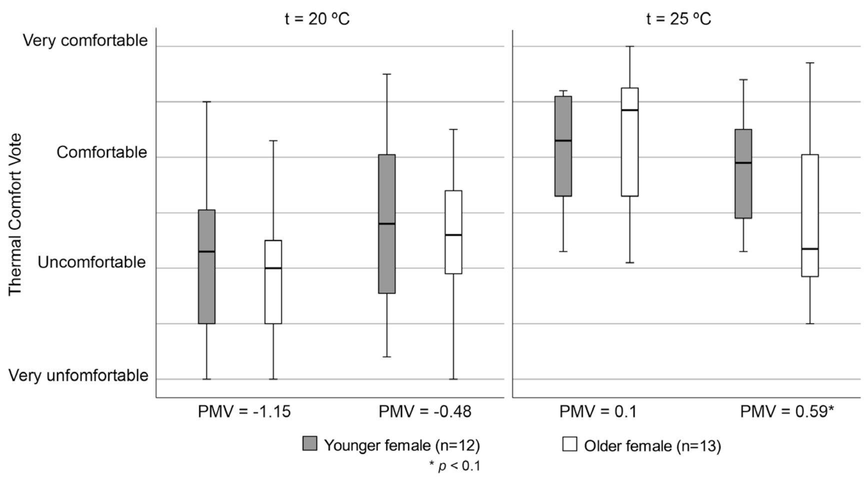

Figure 7. Range of Thermal Comfort Votes between older and younger females

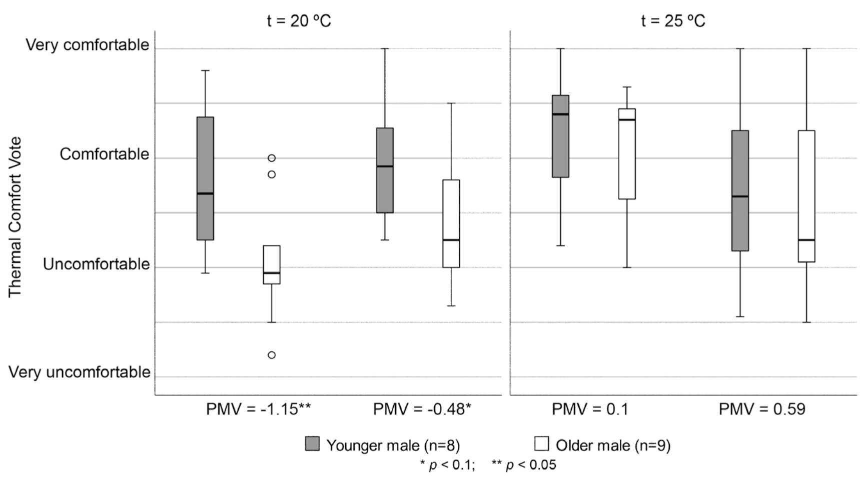

Figure 8. Range of Thermal Comfort Votes between older and younger males

The results also show that for both groups, in most cases the overall thermal comfort significantly correlated with the local thermal comfort on the hand, head and feet (Table 5).

Table 5. Correlations between overall and local thermal comforts

PMV	Group	$R_{overall\text{-}hand}$	*p*	$R_{overall\text{-}head}$	*p*	$R_{overall\text{-}feet}$	*p*
-1.15	Older	0.696**	0.000	0.674**	0.000	0.682**	0.000
	Younger	0.763**	0.000	0.742**	0.000	0.791	0.000
-0.48	Older	0.719**	0.000	0.330	0.134	0.745**	0.000
	Younger	0.824**	0.000	0.919**	0.000	0.818**	0.000
0.1	Older	0.771**	0.000	0.756**	0.000	0.619**	0.005
	Younger	0.668**	0.005	0.697**	0.003	0.309	0.245
0.59	Older	0.705**	0.001	0.901**	0.000	0.417	0.076
	Younger	0.854**	0.000	0.954**	0.000	0.531*	0.028

** Correlation is significant at 0.01 level
* Correlation is significant at 0.05 level

3.3. *Thermal acceptability*

The Shapiro-Wilk tests for normality showed that the mean Thermal Acceptability Votes (TAV) for the older and younger subjects was not normally distributed ($p = 0.005$). At 20 °C set point temperature, the median (first and third quartile) of TAV of the whole group was 0.45 (-1, 0.575) and at 25 °C the median TAV was 1.2 (-0.20, 2.00). Using non parametric tests, significant different was found in the overall median TAV between the older and younger subjects ($p = 0.05$) due to a significant difference at PMV proxy of -0.48 (O = -0.55 (-1.00, 0.32); Y = 0.70 (-0.37, 1.57); $p = 0.03$) even though at PMV proxy of -1.15, no significant difference was found (O = -0.55 (-1.02, -0.2); Y = -0.50 (-1.22, 0.92); $p = 0.57$). There was no significant difference in the overall median TAV between older and younger subjects at set point temperature of 25 °C, PMV proxies = 0.1 and 0.59 ($p = 0.99$, $p = 0.20$ and $p = 1.00$).

Overall, thermal acceptability was the same between female and male subjects within the same age group for all test conditions. Likewise, no significant difference was found in the thermal acceptability between older and younger females as well as between older and younger males.

3.4. *Thermal preference*

The study found no significant difference between the two age groups in their thermal preference (TP) at all four test conditions ($p > 0.05$). However, as shown in Figure 9, at PMV proxy = -1.15 and PMV proxy = -0.48, the proportion of older subjects wanting to be warmer was slightly higher than younger subjects, and at PMV proxy = 0.59, also a higher proportion of older subjects wanted to be cooler. It is interesting to note that there was a small proportion of the older subjects still wanting to be warmer at PMV proxy = 0.59.

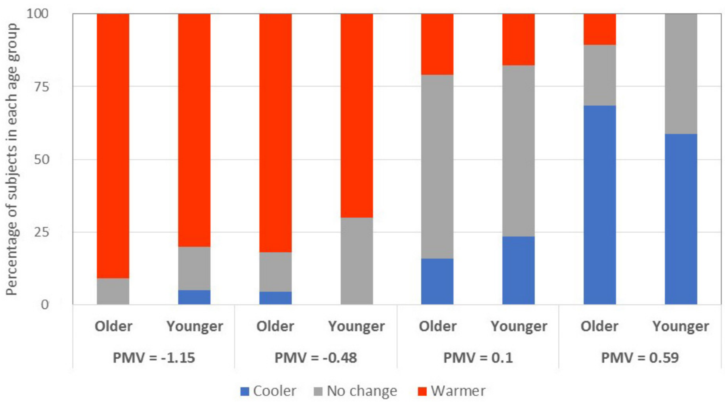

Figure 9. Thermal Preference Votes of older and younger subjects in all four test conditions

The preferences for each gender group were further analysed (Figures 10 and 11). It is worth noting that the proportion of older female subjects (Figure 10) wanting to be cooler or having no change to the thermal condition was higher than that of older male subjects (Figure 11), even at the lower set point temperature. Some of the older female respondents indicated that they were experiencing 'hot flushes' during the test, which may explain the preference to be cooler.

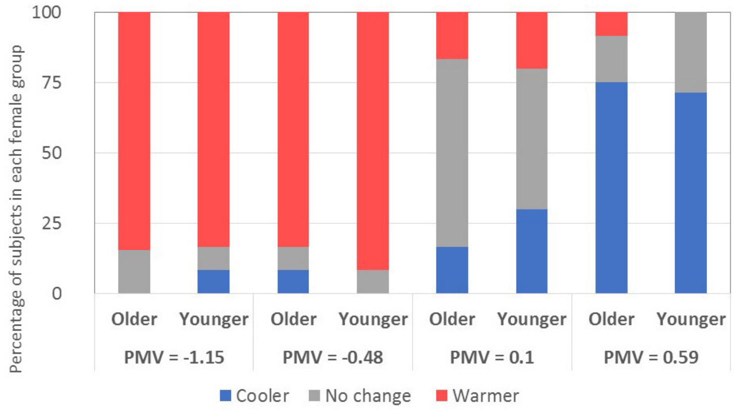

Figure 10. Thermal Preference Votes of older and younger females

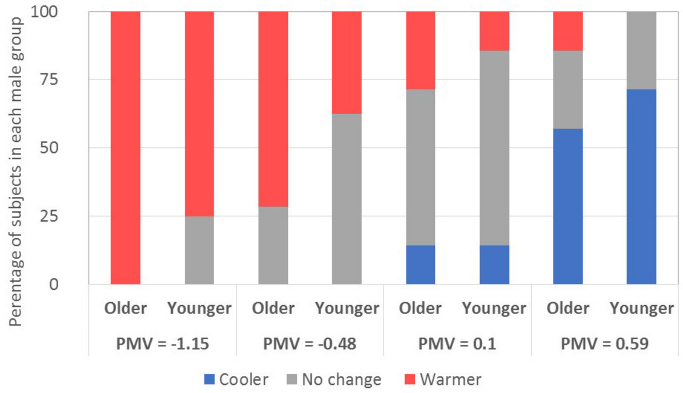

Figure 11. Thermal Preference Votes of older and younger males

3.5. *Frailty*

Based on the Edmonton Frail Scale, among older subjects, four participants scored 0, eight scored 1, one scored 2, three scored 3, three scored 4, and one each scored 7, 8 and 9. This means two subjects were considered to have 'mild frailty', one in the category of "vulnerable" and the rest were not considered frail. All but one of the younger subjects were not frail, and one was considered vulnerable. The Shapiro-Wilk tests of normality shows that the frailty scores were not normally distributed ($p > 0.05$).

Using non parametric correlation tests, the study found no significant correlation between the frailty level, and either of TSV, TCV, TAV and TP ($p > 0.05$); however, not unexpectedly, the frailty score was found to have a significant correlation (2-tailed significance at 0.05 level) with age (Kendall's tau-b correlation coefficient of 0.14 ($p = 0.02$); Spearman rho correlation coefficient of 0.19 ($p =0.02$)) and body weight (Kendall's tau-b correlation coefficient of 0.15 ($p = 0.01$); Spearman rho correlation coefficient of 0.20 ($p =0.01$)). The frailty score was found to increase as the participant's body weight increased and as age increased. It should be noted that this study did not find any correlation between age and body weight ($r = 0.07$, $p = 0.40$) thus they are considered valid independent variables to explain the frailty score.

3.6. *Skin temperatures*

Skin temperatures were measured on the subjects' left hand, right shin, right scapula and the back of the neck. The Shapiro-Wilk tests for normality showed that all measured skin temperatures were normally distributed. Table 6 summarises the mean skin temperatures and standard deviations of both groups at all PMV proxies. As expected, skin temperatures increased as PMV increased.

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https://escholarship.org/uc/item/00h9x985

Overall, older subjects' hand's skin temperature was 0.8 °C higher than the one of younger subjects ($p = 0.04$). At set point temperature of 20 °C, the mean hand's skin temperatures of the older subjects was higher than that of the younger subjects at PMV proxy = -0.48 (O = 30.5° C, Y = 28.7° C, diff = 1.8° C, $p = 0.02$) but not at PMV proxy = -1.15 (O = 29.2° C, Y = 28.3° C, diff = 0.9° C, $p = 0.21$). At set point temperature of 25° C, the difference was not significant ($p > 0.1$). There was also no significant difference between the hand's skin temperatures of older and younger females, and between the older and younger males ($p > 0.1$) except at PMV proxy = -0.48 ($p < 0.05$).

In the older group, the mean of female subjects' hand's skin temperatures was significantly lower (by 2 °C) than that of the male subjects at PMV proxy = -1.15 ($p = 0.04$) and PMV proxy = -0.48 ($p = 0.05$). It was similar at PMV proxy = 0.1. Interestingly, it was slightly higher at PMV proxy = 0.59 although the difference was not statistically significant. In the younger group, at PMV proxy = -0.48 ($p = 0.005$) the female's mean hand's skin temperature was 3.1 °C lower then male. At the other PMV proxies, the differences were not statistically significant ($p > 0.1$).

Overall, no significant difference was found in the neck's, scapula's, and shin's skin temperatures between the two age groups and between female and male subjects. To conclude, in the cooler conditions (at 20 °C set point temperature), older people had higher hand's skin temperatures than younger subjects and females had lower hand's skin temperatures than males.

Table 6. Mean Skin temperatures (and standard deviations) during the tests

	Older		Younger	
	Male	Female	Male	Female
PMV = -1.15				
Hand	30.5 (1.6)	28.5 (2.0)	29.8 (1.5)	27.5 (1.9)
Neck	34.0 (1.5)	33.4 (1.3)	33.6 (1.4)	33.1 (1.2)
Scapula	31.9 (4.5)	32.6 (0.8)	33.3 (1.2)	33.1 (1.0)
Shin	29.7 (3.6)	29.7 (3.2)	31.0 (1.2)	29.8 (1.2)
Average	30.8 (2.7)	31.6 (1.3)	32.2 (0.7)	31.2 (0.7)
PMV = -0.48				
Hand	31.8 (2.2)	29.7 (2.2)	30.5 (1.0)	27.4 (2.0)
Neck	34.3 (1.1)	34.3 (1.4)	34.1 (0.8)	34.6 (1.0)
Scapula	34.0 (1.4)	33.1 (1.5)	33.7 (1.1)	33.9 (1.1)
Shin	31.2 (1.5)	30.2 (1.8)	30.5 (0.6)	29.8 (1.2)
Average	32.8 (0.5)	31.9 (1.1)	32.4 (0.5)	31.9 (0.9)
PMV = 0.1				
Hand	32.3 (0.7)	32.2 (1.0)	32.8 (1.0)	31.6 (1.5)
Neck	35.2 (0.8)	34.4 (1.0)	34.8 (0.4)	35.3 (0.9)
Scapula	34.0 (1.1)	34.3 (0.5)	34.3 (0.7)	34.9 (0.5)
Shin	33.0 (0.5)	32.9 (0.8)	32.5 (1.0)	32.5 (0.7)
Average	33.8 (0.5)	33.6 (0.6)	33.7 (0.5)	33.8 (0.6)
PMV = 0.59				
Hand	32.8 (0.7)	33.1 (1.1)	33.2 (1.0)	32.2 (1.6)
Neck	35.6 (0.6)	35.3 (0.9)	35.3 (0.7)	35.8 (0.6)
Scapula	34.4 (1.2)	34.9 (0.5)	34.9 (0.5)	35.3 (0.5)
Shin	32.9 (0.7)	33.0 (0.8)	32.7 (0.9)	32.6 (0.7)
Average	34.1 (0.5)	34.2 (0.6)	34.1 (0.5)	34.2 (0.5)

4. Discussion

4.1. Thermal sensation, comfort, acceptability and preference comparing older and younger groups

Overall, there was no significant difference in the TSV between the two age groups ($p > 0.05$). This result is similar to a number of previous studies conducted in environmental comfort chambers [18, 19, 20, 21]. The result is confirmed through a post hoc power analysis, which shows an observed power of 0.088 and effect size (η) of 0.002, indicating that the difference was trivial.

We plotted the relationships between the four proxies of predicted mean vote (PMV) and the mean thermal sensation votes (TSV) of all the older and younger subjects (Figure 12). In both older and younger subjects, the TSV slopes are slightly steeper than the PMV slope ($F_{older} = 35.61$, $p < 0.00$; $F_{younger} = 26.41$, $p < 0.00$). The slope for the older subjects appear to be slightly steeper than that for the younger subjects, with the mean TSV of the older subjects at PMV proxy of -1.15 being 0.38 less than that of the younger subjects but identical at 0.59 PMV proxy; however, the difference between the two slopes is not statistically significant ($t = -0.68$; $p = 0.50$).

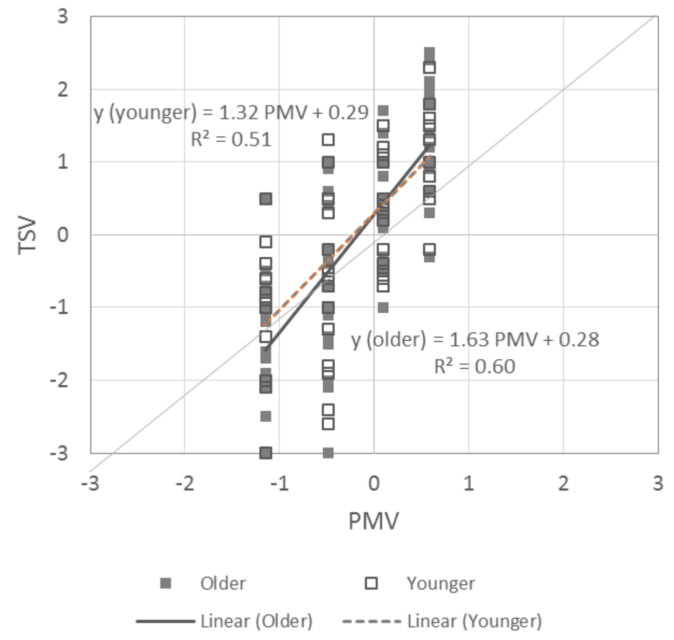

Figure 12. Predicted Mean Votes vs Thermal Sensation Votes of older and younger subjects at four test conditions

For thermal comfort, a statistically significant difference was found in their overall thermal comfort and at PMV proxy of -1.15 only, particularly due to the significant difference between the older and younger subjects within the same sex group. This is also confirmed through a post hoc power analysis, showing an observed power of 0.595 and 0.435 for the overall and PMV proxy -1.15, respectively; however, the effect size was small (η = 0.028 and η = 0.073, respectively). Interestingly, the difference between the older and younger females was found in the slightly warm condition, at PMV proxy of 0.59, with the older subjects perceiving the condition to be uncomfortable whereas the younger subjects perceived it to be slightly comfortable, whereas the difference between the older and younger males was found in the slightly cool and neutral conditions, at PMV proxies of -1.15 and -0.48.

Overall thermal acceptability between the two groups was found to be significantly different at 20 °C set point temperature ($p < 0.05$, observed power = 0.727, η = 0.076), but not at 25 °C set point temperature ($p > 0.05$, observed power = 0.139, η = 0.011). Likewise, no statistically significant different was found in thermal preference between the two age groups ($p > 0.05$, observed power = 0.104, η = 0.03).

4.2. Correlations with skin temperatures

For both older and younger groups, thermal sensations had significant correlations with all four measured skin temperatures (correlations were significant at either 0.01 or 0.05 level), but the highest correlation with thermal sensation was with the hand's skin temperatures. This is consistent with the result when looking at the correlations between local and overall thermal sensation votes, with thermal sensation on the hand had the highest correlation with the overall thermal sensation. These results are in line with

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much earlier work by Zhang [48] and more recent work by Dai et al. [49] which showed the high correlation between hand's skin temperature and overall thermal sensations, and with Bae et al. [50] which found that in the 30 older subjects in Korea, there was a strong correlation between thermal sensation and local skin temperature on the back of the hand.

For the older group, thermal comfort and thermal acceptability had stronger correlations with the shin's skin temperature (r = 0.37, p = 0.00 (thermal comfort); r = 0.35, p = 0.00 (thermal acceptability)) followed by the hand's skin temperature (r = 0.32, p = 0.01 (thermal comfort); r = 0.33, p = 0.00 (thermal acceptability)). For the younger group, thermal comfort had a stronger correlation with the shin's skin temperature (r = 0.36 p = 0.00), followed by the hand's skin temperature (r = 0.30, p = 0.01), but their thermal acceptability was mostly correlated with their hand's skin temperature (r = 0.32, p = 0.01), followed by the shin's skin temperature (r = 0.31, p = 0.01). For the older subjects, thermal preference was found to be mostly correlated with the shin's skin temperature (r = -0.46 p = 0.00), but for the younger subjects it was the hand's skin temperature that had the strongest correlation with thermal preference (r = -0.682, p = 0.00).

In summary, it can be said that for both groups, the hand's and shin's skin temperatures had the strongest correlations with thermal sensation, comfort, acceptability, and preference, with some slight differences in the strength of the correlations between these factors.

4.3. Frailty and thermal comfort

The study found significant correlations between age and body weight with the frailty score, but did not find any significant correlation between the frailty level of the subjects and their thermal comfort. This may be due to the fact that only two subjects were predicted to be in the category of 'mild frailty' according to the Edmonton test (scored 8 and 9), and only one was identified as being 'vulnerable' (scored 7), while the rest were identified as 'not frail'. Interestingly, a participant predicted to be 'vulnerable' was also found in the younger participant group. It is also possible that due to the way the subjects were recruited (that is through email lists, social media, as well as senior centres and church) and the way the background survey was conducted (that is through an on-line survey system), only those who were more active in society and computer literate responded to the invitation to participate in the study and that these people tended to be less frail.

5. Limitations

The number of subjects in the study was 22 for the older group and 20 for the younger group. When divided based on sex, the number of subjects in each sub group was even smaller, about half these values. Considering that there is a wider range of body build among people, particularly of the older group, which would affect thermal comfort and sensation, a larger number of subjects with different body build would be valuable.

Further, as we attempted to minimize the discomfort experience from having many skin temperature sensors placed on the body, particularly among the older subjects, we followed ISO9886 procedure of 4-point measurements (at the back of the neck, right scapula, left hand, and right shin), which was recommended for warm and hot conditions. This is a limitation of the current study, as in cooler conditions, extremities are likely to result in low skin temperatures due to vasoconstriction. Therefore, in future studies under cool conditions, the 8 or 14-points approach should be used to capture temperatures extremities, especially on the foot, which is missing in the 4-point approach.

6. Conclusion

We investigated, in an environmental chamber involving 22 older and 20 younger subjects, whether there were differences in the thermal sensation, comfort, acceptability and preference between the older and younger groups. The study also investigated whether the subjects' thermal comfort, particularly from the older group, correlated with their frailty score. The subjects were exposed to four test conditions, representing PMV of -1.15, -0.48, PMV = 0.1, and 0.59.

Results from the study can be summarised below:

- The thermal sensation and preference for older and younger subjects were the same at all tested conditions except thermal sensation was different at PMV proxy of -0.48, with the younger males having almost 1 TSV higher than the older males.
- Thermal comfort of older and younger groups differed only for overall and at PMV proxy of -1.15, with the older group perceiving the condition to be less comfortable at 0.8 of a scale than the younger group.
- Thermal acceptability of older and younger subjects was the same except for overall and at PMV proxy of -0.48, with the older subjects perceiving the condition to be less acceptable.
- In both older and younger subjects, the hand's skin temperatures had significant correlation with the local and overall thermal sensation.
- At 20 °C ambient temperatures, for both age groups, male hand skin temperature is about 2K higher than female's.
- Subjects' frailty level was not correlated with their thermal sensation, comfort, acceptability and preference but we did not have many frail subjects.

In conclusion, the study found no significant difference in many test conditions between the thermal sensation, comfort, and acceptability of older and younger subjects. Considering that some previous lab studies did find differences in the thermal sensation and preference between older and younger subjects [22, 23, 24, 25] while others found the opposite [18, 19, 20, 21], future research in this topic as well as a meta-analysis is worth pursuing. We also did not find significant correlations between thermal sensation, comfort, acceptability, preference and frailty level, and part of the reason is that we did not have a sufficient number of frail subjects. However, considering the importance of this issue, particularly as our population is ageing, further studies on this topic are needed. Designing a living environment that provides the thermal comfort that older people need without an unacceptable cost burden can only be achieved if we understand their thermal comfort, acceptability and preference.

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