Thermal comfort modelling of older people living in care homes: An evaluation of heat balance, adaptive comfort, and thermographic methods

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Thermal comfort modelling of older people living in care homes: an evaluation of heat balance, adaptive comfort, and thermographic methods

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Abstract

Older adults are more thermally vulnerable than the younger adults that comfort metrics tend to be empirically drawn from. They are less able to discriminate between warmth and cold and those that experience motor or neurological impairments may be less able to perceive or communicate their thermal sensation and preference; placing the onus of thermal regulation on their carers. This situation is accentuated as societies age, so that there is a growing need for guidance for the thermal regulation of care homes; to establish whether existing metrics may be used with confidence or whether the evidence base needs to be extended to encompass data from older adults. To this end, this paper presents a study of three approaches to thermal comfort modelling for older age care home residents: (1) Predicted Mean Vote (PMV), (2) Adaptive Comfort, and (3) long wave infrared thermography (IRT). Based on measurements from a previous field survey, our results show that (1) PMV can, in principle, be applicable to older people, but procedures for estimating metabolic rates are outmoded and summertime conditions tend to be free-running; (2) Adaptive Comfort appears to be well suited and can also consider feedback from adaptive actions; (3) The difference in skin temperature obtained from infrared maps of the upper extremities (hands, wrist, forearm) has potential as an indicator of thermal comfort, if these measurements can be practically deployed. However, all three approaches are limited in their ability to account for the distribution of thermal sensations collected from subjects with dementia.

Keywords: Predicted Mean Vote (PMV); adaptive comfort; infrared thermography; dementia; thermal comfort; residential care homes

1. Introduction

The global population of people aged 65 years or over is projected to approach 1.5 billion by 2050 [1]. In the UK, it is estimated that by 2037 approximately 24% of the population will be aged 65 years and over, compared to 18.2% in 2017 and 15.9% in 1997 [2]. For over a decade, there have been concerns about the UK's ageing society, especially the rising number of older people requiring long-term care [3]. Thus, the provision of residential care by care home service-providers is of increasing importance as societal demographics change [4].

As people age, the health risk of exposure to rapid or extreme changes in environmental temperature present challenges for thermal homeostasis [5, 6, 7]. Thermal stress, due to either indoor (and outdoor) cold or heat strain, is a potential health hazard [8] especially for older people with multiple co-morbid conditions. Furthermore, the increased vulnerability to heat as people age exacerbates heat-related morbidity and mortality [9] making residents susceptible to the effects of changes in the thermal environment [10, 11]. This makes it important to tailor indoor environmental conditions to meet the thermal needs of residents, a crucial consideration for health and wellbeing.

Older people are generally considered to suffer from impairment of temperature regulation, making them susceptible to the impact of even moderate fluctuations in outdoor (and indoor) temperature [12] [13]. Continued exposure to unfavourable room temperatures can have an adverse impact on pre-existing disease and health conditions especially under extreme weather changes (cold snaps [14] and heat waves [5]). This, coupled with a diminution of temperature discrimination means that older people may not be aware of how cold, or hot, they are [15]. Furthermore, for those who are unable to communicate their feelings, as in stroke or dementia, the ability to perceive (and report) thermal sensation increases the risk of thermal discomfort and attendant emotional and health consequences [16]. This places greater emphasis on others, particularly carers, to make choices for the older person with respect to clothing insulation and garments as well as adjusting room temperature [17].

Now, as societies age, and many more people are living in residential care [18], there is an increasing need for provision of indoor environment guidelines tailored to vulnerable older people [15]. Having a reliable indicator to assess or predict an older persons' indoor thermal sensation is crucial in helping to create a thermal environment which meets comfort conditions as well as providing an optimum indoor temperature for the living space [19, 20]. How this is achieved in the setting of residential care presents a major challenge for residents with advanced age or health conditions, specifically with respect to their ability to perceive a change in the thermal conditions of their immediate environment which, day to day, is typically controlled entirely by younger staff [15]. In addition, care home residents with dementia may be unable to communicate verbally, or reliably, their satisfaction with indoor environmental conditions [21].

Indoor thermal comfort standards such as EN ISO 7730 [22] and ASHRAE 55 [23] are widely in use to assess or predict occupants' thermal comfort levels and no distinction is made by age. However, these standards were mainly established through measurements made upon 'healthy' adults. Although studies revealed these standards may be applicable to elderly people [24, 25], it remains unclear whether they are sufficiently reliable to predict thermal comfort for older, often frail individuals, living in residential care [26, 27]. Their practical deployment is also complicated by difficulties in measuring metabolic rate [28]. There is thus a need to carefully assess the applicability (or practicability) of existing thermal comfort models/methods to care home setting.

In this paper, based on the measurements collected previously from a field survey undertaken in multiple United Kingdom (UK) care homes, a study of three thermal comfort modelling methods is presented: (1) Predicted Mean Vote (PMV), (2) Adaptive Comfort, and (3) Infrared Thermography (IRT). Therefore, this study aims to evaluate their potential utility to the care home setting as a pilot study, and finally to inform the research design of a large fieldwork campaign acquiring a rigorous evidence base to support thermal design and control for the care home sector.

2. Thermal comfort for older recipients being cared

A literature review was first carried out to address (1) what we know about thermal environment and thermal comfort within the senior 'care' homes, and (2) why those abovementioned three thermal comfort approaches need to be evaluated for care home setting. Thus, this section is to identify a clear research gap between the existing thermal comfort models/methods and the requirements of the thermally comfortable environment for older recipients being cared by younger adults.

2.1. People in care homes

As people age, there are rising numbers of older people requiring long-term care, particularly older people with frailty, dementia or both [3]. Care homes provide a homelike residential place with 'care', and in the UK, they are divided into residential homes and nursing homes, funded by the UK National Health Service (NHS) or private businesses [29]. Residential homes provide shelter and personal care, such as washing, dressing, toileting, feeding and mobility plus administration of prescribed medication. The main distinction between residential care and nursing care is the provision of one or more qualified nurses on duty to provide nursing care in addition to personal care, including for those with learning disabilities and/or severe physical disabilities. Some nursing homes offer special services for people who may need more supervised care: for example, the elderly mentally infirm (EMI).

People in care homes cannot simply be described by 'old'. The World Health Organisation (WHO) [30] explains that ageing accompanies biological changes, but the changes are complex [31], with progressive accumulation of a wide range of molecular and cellular damage [32, 33], which however is not linearly and consistently associated with age in years [32]. This suggests large variations of physiological function individually in thermal regulation responding to the ambient thermal environment.

The 'thermal environment' can be described as the characteristics of the environment that affects the heat exchange between the human body and the environment [16]. One distinctive environmental characteristic of care homes is that the indoor thermal condition is typically controlled entirely by 'others' (carers or staffs), whose age is younger than those being cared. This is potentially problematic to people with dementia (or learning disabilities) who are unable to sense and communicate reliably their satisfaction with indoor thermal conditions; a capacity that diminishes with cognitive function [34]. ASHRAE [23] defines thermal sensation as a conscious feeling, which requires subjective evaluation, and thermal comfort is defined as the state of mind which expresses satisfaction with the thermal environment. The subjective expression of thermal sensation and comfort potentially differs from the biological response to the thermal environment, leading to adverse health outcomes and wellbeing [35]. The effective provision of thermally comfortable conditions can thus be challenging even without cognitive or physiological dysfunction.

Studies have revealed that the optimum temperature of older people to achieve thermal comfort is higher than that of young adults with equivalent clothing insulation, owing to lower metabolic heat production [36, 37, 38, 39]. Furthermore, females tend to be more sensitive to cold temperatures and hence to prefer warmer temperatures [40, 41, 42]. However, this distinction is not well established for older-old, often frail or older people with dementia in care homes, with differing thermal perceptions and sensitivities [16, 43].

2.2. Thermal comfort models into care home setting

2.2.1. The Predicted Mean Vote

Developed by Fanger [44], the Predicted Mean Vote (PMV) is the basis for multiple standards for assessing building occupants' indoor thermal comfort [22, 23, 45]. It was developed under the steady-state conditions of the climate chamber and based on the results of 1396 college-aged adult subjects. By contrast, validation of the PMV for application to older people was undertaken with a much smaller sample; 128 older subjects [44].

Based on available studies [21, 22], ASHRAE [47] state that the PMV model for thermal comfort assessment is applicable for young and old alike. This, it is claimed, is because metabolic rate clothing choices account for the effects of age (and gender) in PMV estimations [12]. Ageing decreases resting metabolic rate (RMR) [48, 49]. A reduction in heat production accounts for the lower body temperature in older people [12], leading to the need for thicker clothing to increase body insulation in older people [50, 51]. Typically, RMR declines at a rate of 10% per decade from age 3 to over 80 for males [52], or 10-15% per decade for females with a similar body size [53]. However, these studies date back some 40-60 years, when like expectancy was significantly lower.

The key determinants of the PMV model consist of four indoor climate parameters (ambient air temperature, relative humidity, mean radiant temperature and air speed) and two personal factors (clothing insulation and metabolic rate). Each PMV variable has a certain boundary, as specified in ISO 7730. This is to avoid a biased PMV outcome contributed to by a single or combined multiple variables

[54]. Thermal comfort is assumed to occur at thermal neutrality; specifically at $-0.5 \leq PMV \leq 0.5$ [23]. For sensitive and frail people, EN 15251 [45] suggests a range of $-0.2 \leq PMV \leq 0.2$ for thermal comfort.

Table 1. PMV Predictors' boundary conditions in application to be free from bias (Source: [54]).

Predictors	ISO 7730	Humphreys and Nicol, 2002
Indoor air temperature (T_a, °C) & mean radiant temperature (MRT, °C)	10-30 for T_a; 10-40 for MRT, 35°C of upper limit of operative temp	Upper limit of operative temp: 8K lower than ISO 7730
Relative humidity (%)	30-70	Below 60
Air speed (m/s)	0-1	0-0.2
Metabolic rate (MET)	0.8-4.0	Below 1.4
Clothing insulation (clo)	0-2.0	0.3-1.2
Daily mean outdoor temperature (°C)	-	Biased at 5-10; <12; >25

Recent field studies have shown that there is an argument against the applicability of PMV to older people. Wang et al. [55] indicated that the PMV for older people (aged 64 – 76 years) is inconsistent where the PMV is less than -1. Furthermore, in a care home field study (398 subjects aged 65 - 90 in 26 care homes) in South Korea [56], the applicability of PMV in the cooling season (summertime) is poor compared to the heating and mid-seasons.

PMV is particularly sensitive to air speed, clothing insulation (c*lo*) and metabolic rate (MET). Thus, inaccurate measurements (or assumptions) result in an incorrect interpretation of PMV-based thermal comfort assessment [54, 28]. Put simply, for precise thermal comfort assessment, a precise measurement of metabolic rate is also required, below 2 MET particularly [28]. Furthermore, Brager et al. [57] found that *clo* can vary by up to 0.1 units depending on the standards and algorithms used in its calculation.

2.2.2. Adaptive comfort

As the PMV model was developed under the controlled conditions of an indoor climate chamber, its use may be best suited to air-conditioned buildings (Table 1). Where the indoor environment of buildings in warm climates is not air-conditioned, previous field studies show that PMV predicts a warmer predicted thermal sensation than that 'perceived' by the occupants, suggesting that PMV overestimates thermal sensation in these circumstances [27, 28]. As a result, efforts were made to adjust PMV to extend its applicability to non-air-conditioned buildings using an *expectancy factor* (*e*), to account for an occupants' local climate adaptation [60].

Also, particularly for a naturally ventilated building, the adaptive method [61, 62] accounts for local climatic adaptation by season. The only determinant here is outdoor temperature but there are multiple versions of adaptive thermal models using different measures of outdoor temperature: daily mean outdoor temperature in CIBSE Guide A [63] and monthly mean outdoor temperature as recommended in ASHRAE 55 [23] based on the findings from de Dear and Brager [64]. Furthermore, Nicol and Humphreys [65] suggested the use of an exponentially weighted running mean of outdoor temperature. A drawback of this approach, however, is that predictions of neutral temperature are independent of the specific characteristics of the building being occupied or of the characteristics of the population occupying it and their associated behaviours [66].

As a further development of the adaptive method, Haldi and Robinson [66] proposed a framework which unifies thermal perception and adaptive actions, explicitly incorporating feedback on thermal sensation of specific adaptive behaviours to maintain or restore thermal comfort. However, the assumptions about residents' voluntary or involuntary adaption actions can be questionable under biological ageing compounded with underlying personal health conditions. Specifically, residents with dementia may have difficulty in perceiving their thermal discomfort correctly and in taking adequate actions to restore their thermal comfort.

2.2.3. Thermographic method

As discussed by Hoof et al. [15] and Childs et al. [21], there is a clear need for easily deployable techniques to allow carers to make timely assessments and for them to take adequate actions to help the resident to achieve thermal comfort. Currently, there lacks a reliable indicator to determine a person's thermal sensations physiologically without the need to ask. This is particularly valuable for those who are unable to communicate appropriately due to cognitive decline.

Previous studies have investigated skin temperature as a predictor of thermal sensations (i.e., [36, 37, 38, 39]). In South Korea, Bae et al. [71] found that skin temperatures (cheek, upper arm, back of hand, and top of foot) of older people were strongly correlated with actual thermal sensation in a climate chamber study with 30 subjects (15 males and 15 females), and in their field study (294 older residents in 7 welfare centres) they concluded that cheek and back of hand skin temperature can be used to predict thermal sensations for older people. More recently, Tejedor et al. [72] performed infrared thermography at four face points (nose, forehead, cheekbone, and chin) showing that it is possible to detect thermal neutrality and found that the thermally 'neutral' state is reached when all facial temperatures were equal to 35^{o}C, where the operative temperature is 23.5^{o}C and relative humidity is 54%.

Childs et al. [21] present a case for using IRT to 'see' the thermal map of the extremities and to deduce the corresponding thermal sensation vote. The principle here is that, (under thermally neutral conditions) skin blood flow in the hands is tonically active such that vasomotor tone of skin capillaries operates as the primary 'controller' of deep body temperature. Hands (and feet) represent 'radiator' organs [73] losing heat to the environment as well as retaining and conserving body heat. Skin temperature therefore varies with changes in vasomotor tone, and this is reflected in the appearance of the thermal map through changes in the capillaries. Non-glabrous skin, along with arterio-venous anastomoses (AVAs) of glabrous (hairless) skin of hands and feet are continuously adjusting (cycling) blood flow to extremity skin to balance heat loss with heat retention [43, 44].

It is noteworthy that more than 80% of thermal comfort field studies have focussed on young adults, aged 20-25 [76]. There are very few studies of vulnerable populations in care homes [15] and no studies have comprehensively assessed the applicability (or practicability) of existing thermal comfort models/methods in care home settings.

3. Materials and methods

3.1. The care home field survey and measurements

The field survey and data measurements were performed by Childs et al. [21] with participation from 69 older residents (60–101 years of age) living in 15 residential care homes within the South Yorkshire and Derbyshire counties of the UK, over a 12-month period (June 2017 - June 2018).

3.1.1. Screening and Recruitment Pathway

Older people were invited to submit their written informed consent to participate in the study after having reviewed the participant information sheet. The capacity screening was carried out by research nurses of the clinical research network for the Yorkshire-Humber and Derbyshire National Health Service. Each residence manager was first contacted and the outline of the study was introduced verbally and via leaflets for the care home staff. If the manager expressed an interest in the objectives of the study, a researcher visited the care home to discuss the details of the study. Older participants that were capable of giving their own informed consent were identified by the care home manager. Consent to participate was obtained in every case, either from the participant his/herself or from an authorised representative. A mutually convenient date was then identified for the field survey and associated measurements of each participant.

3.1.2. Data collection

Participants were recruited to two groups: dementia (N=34) and non-dementia (N=35), based on the scores obtained using the 10-point scale of the Abbreviated Mental Test (AMT) [77]. Residents with AMT<8 were assigned to the 'with dementia' group. Participants with a medical diagnosis or clinical presentation of dementia were included, providing that they could understand the questions. Typically, this would be those participants with a dementia score between 6 and 8. As memory and cognition is labile, there are times when people with dementia can participate in studies of this nature, i.e., offer a narrative. Demographic and clinical data included age, gender, and clinical frailty, using a seven-point scale (version 2007-09 Dalhousie University, Halifax, NS, Canada [78]).

The indoor environmental data was collected in the communal areas of each of the care homes, where the Long-Wave Infrared Thermography (IRT) was performed. This included ambient air temperature, relative humidity and air speed (Kestrel 3000, Kestrel Instruments, Boothwyn, PA, USA), with the measurements recorded when commencing thermography. To estimate clothing insulation (*clo*), a weighted valuation of clothing ensembles worn by participants was obtained [79]. Also, body temperature was measured at the tympanum using a thermo-scan device (Model LF 40, Braun, Lausanne, Switzerland) just before commencing thermography.

Long-Wave Infrared Thermography (IRT) was performed using a micro-bolometer detector (model A-600 series, FLIR, Täby, Sweden, image resolution 640×320 pixels). Participants were asked to rest for 15 minutes to avoid the effect of 'movement' on the measurement. The IRT imaging data was obtained from participants' non-dominant hands from fingertip to forearm, sitting comfortably in the communal areas of the care homes: specifically the distal phalange, middle phalange, proximal phalange, metacarpal, capitate bones and distal humerus.

During the IRT measurements, each participant was asked to rate their thermal sensation vote (TSV) using the ASHRAE 7-point thermal sensation scale, ranging from -3 (cold) to +3 (hot). In addition, the McIntyre thermal preference scale [80] was used to obtain a response to the question "I would like to be": (a) cooler, (b) no change, (c) warmer. Thermal preference does not indicate thermal 'neutrality' but it can be used to inform decisions to control (or change) the thermal environment [81]. This study only used the thermal preference vote as a reference for subjects to express their feedbacks regarding their thermal environment where/when it was measured. All measurements were performed one person at a time, meaning that the sample size of each dataset follows the number of subjects: older people with dementia (N=34), older people without dementia (N=35).

A separate field survey was undertaken whereby 17 younger adults (aged 18-34 years) were studied during October 2017 to March 2018 as a comparator group for the older aged adults. Participants were healthy and without pre-existing medical conditions and were volunteers from University and National Health Service (NHS) communities. The same infrared equipment and monitoring set-up was used as for the residential care setting, and the measuring method used for older people was equally applied to young adults. These data are presented in this paper to allow comparisons with the older participants' data.

3.2. The methods: PMV, Adaptive Comfort, and Infrared Thermography

Given the field measurements, we examined three methods for assessing thermal comfort of older people living in residential care: (1) Predicted Mean Vote (PMV), (2) Adaptive Comfort, and (3) Infrared Thermography of extremity skin temperature. A probabilistic approach to modelling thermal comfort based on the actual thermal sensation votes (TSV) was employed. This is to account for the distribution of thermal sensations potentially derived from individual biological ageing and personal expectations compounded with residents' underlying health conditions. We also reviewed the thermal sensation votes collected from the participants with dementia. Thus, samples were divided into people with and without dementia.

3.2.1. PMV-based approach

During the field survey, the mean radiant temperature (MRT) and metabolic rate (MET) of participants were not measured. Here we assume MRT being equivalent to air temperature. Also, in the absence of measured MET, we estimated participants' (and their aggregated) MET by investigating the relationship between actual thermal sensation vote (TSV) and the predicted mean vote (PMV), under the assumption that PMV is applicable to care home residents with two bands of PMV thermal neutrality: -0.5<PMV<0.5 (strictly comfortable) and -1<PMV<1 (loosely comfortable).

As TSV was surveyed where the subjects were typically sedentary, the estimated MET would be expected to be below 1.2 under the PMV applicability assumptions to care home subjects. In cases where the estimated MET was out of the sedentary threshold (1.2 MET), further analyses were required to identify a possible threshold of comfort PMV for care home residents under the assumption that their body size is not different from "average adults" of 30 years old: male (70kg, 175cm, 1.8 m^2 of body surface area); female (60kg, 170cm, 1.6m^2 of body surface area). The MET can be estimated by the following expressions:

- MET = EER/RMR
- EER for male = 864 – 9.72×Age (years) + PA(14.2×Weight (kg) + 503×Height (m))
- EER for female = 387 – 7.31 (years) + PA(10.9×Weight (kg) + 660.7×Height (m))
- RMR = 10×Weight (kg) + 6.25×Height (cm) – 4.92×Age (year) + 166×Gender -161, (Female=0, Male=1)

Where EER is the estimated energy requirement (Kcal/day) [82], RMR is the resting metabolic rate (Kcal/day) [83], and PA is a physical activity coefficient (sedentary: PA=1, low active: PA=1.12 (1.14) for male (female), active: PA=1.27, and very active: PA=1.54 (1.45) for male (female) [82]).

3.2.2. Adaptive comfort approach

We selected the adaptive comfort modelling framework suggested by Haldi and Robinson [66], which unifies thermal perception and adaptive actions to maintain or restore thermal comfort[1]. The rationale is that an adaptive comfort model can potentially account for individual distributions in thermal sensations alongside personal adaptive actions and expectations in the care homes, where residents spend the majority of their time indoors. Here, we utilised logistic regression techniques for modelling the distribution of thermal sensations to probabilistically deduce indoor air temperatures for thermal comfort. As evidenced in Figure 3 (b), it shows that residents without dementia seem capable of taking action to maintain (or restore) their thermal comfort, i.e., clothing selection according to the indoor air temperature. Also, according to the thermal preference vote, about 80% (N=28/35) of residents without dementia did not want to change their existing indoor thermal conditions. These circumstances seem to suggest a case for adaptive thermal comfort by modelling both occupants' behaviours and the feedbacks of these behaviours relating to their thermal sensations.

3.2.3. Infrared thermography of extremity skin temperature

Adaptive comfort modelling of thermal sensations may reflect care home residents' overall thermal comfort. However, it may not be adequate to serve as a common guideline for care homes, considering

[1] Although this does in principle support building and population specific predictions (irrespective of building types), doing so effectively in practice would require a substantially larger dataset than was available to us, to substantiate the framework.

the assumptions about residents' voluntary or involuntary adaption actions, i.e., people with dementia. In line with a clear demand for easily deployable measures, which allows carers to take timely and adequate actions to maintain or restore their residents' thermal comfort, we investigated how the measured long-wave infrared thermography (IRT) data of a non-dominant hand can help to assess (or predict) thermal comfort for older people in care homes.

From the thermal map of the IRT image, the mean temperature differences (°C) between distal phalange (T_{Dp}), capitate bones (T_{Cap}) and distal humerus (T_{Dh}) was calculated as $\Delta T_1 = T_{Dp} - T_{Cap}$, and $\Delta T_2 = T_{Dp} - T_{Dh}$. The rationale of considering ΔT_1 or ΔT_2 is that a significant threshold of thermal comfort may be determined at some point where the temperature difference between finger to forearm may indicate a persons' thermal sensation and comfort [84].

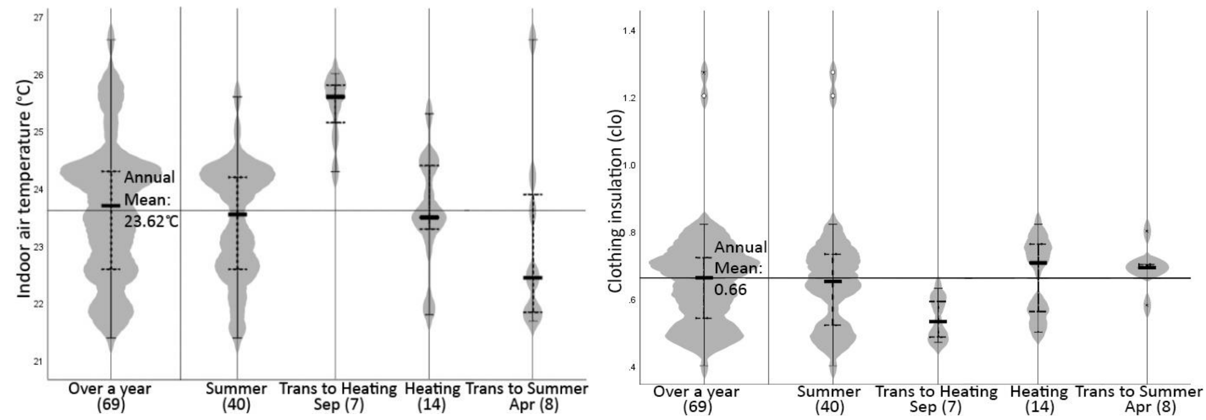
Here we again employed probabilistic thermal comfort modelling, but now to identify a possible thermographic threshold of thermal comfort for older people in care homes. In this way, we assess the potential utility of thermography as an additional assessment technique for care home settings, using the results from Childs et al's feasibility study [21], in conjunction with the further measurements of young adults mentioned above.

The results from the PMV, Adaptive Comfort and Infrared thermography methods are presented in Section 4. Our intention was to assess the applicability of the three approaches to care home setting as a pilot study and to discuss the practicability of their deployment in care homes and thus to inform the research design of a large fieldwork campaign with which to develop a rigorous evidence base to support thermal environment management in this little studied setting.

4. Results

4.1. Characteristics of the indoor thermal environment in the care homes

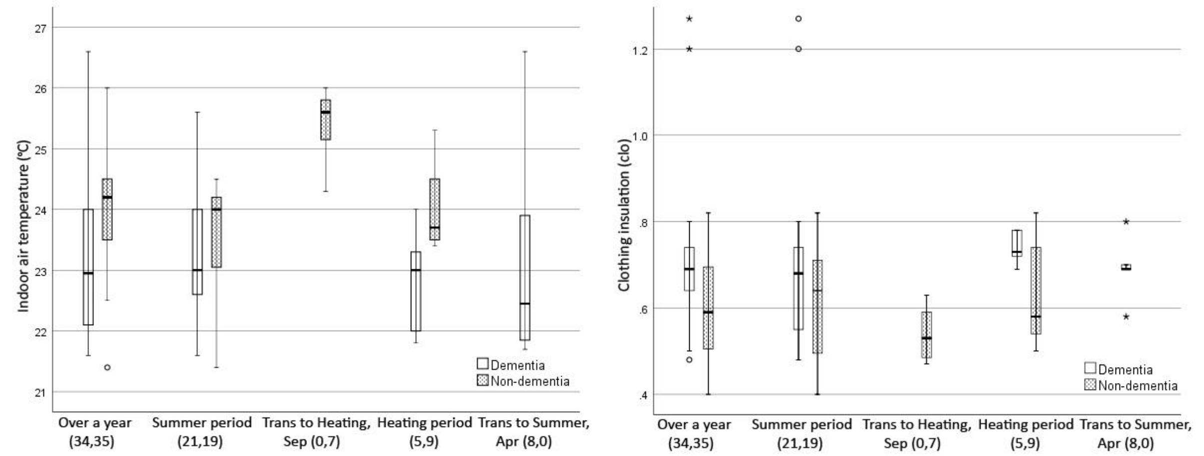
The seasonal variance of indoor air temperatures in the 15 care homes is shown in Figure 1 (a). The annual timeline is divided into four periods: summer (May to August), 'transition to heating' (September), 'heating' (October to March) and 'transition to summer' (April). Transition months (September and April) were added between two major seasons as a relatively inconsistent distribution was found in comparison to heating and summer periods. The range of indoor air temperature over a year was 23.62 (Mean) ± 1.21°C. In heating and summer periods, the temperature was similarly distributed: 23.60 ± 0.95°C in heating and 23.42 ± 1.01°C in summer period, respectively. The clothing insulation (*clo*) had an opposite pattern to air temperature as shown in Figure 1 (b).



(a) (b)

Figure 1. Seasonal variance in (a) indoor air temperature (°C) and (b) Clothing insulation (*clo*) collected in 15 care homes over a year. Each Notch indicates 25% from the median (thick solid line) and () is number of samples.

A one-way between-groups analysis of variance (ANOVA) was performed to explore the seasonal impact on indoor air temperature and clothing insulation. The two transition periods were excluded, owing to a lack of clarity of the seasonal classification and the relatively small number of measurements at these time point (N=7 in September and N=8 in April). There was no statistically significant difference at the $p < .05$ level in indoor air temperature and clothing insulation for heating and summer periods: $F(1,52) = 0.342$ with $p = 0.561$ (indoor air temperature) and $F(1,52)= 0.007$ with $p = 0.936$ in (clothing insulation). This suggests an absence of adaptation. However, this does not confirm that the indoor thermal environments of the 15 care homes surveyed were maintained at a consistent temperature during the 12-month study period, even excluding April and September. To confirm if there is consistency of indoor temperature over a year, a further field study is required to establish the details of heating and cooling practice in care homes (including also opening/closing windows and doors for natural ventilation).



(a) (b)

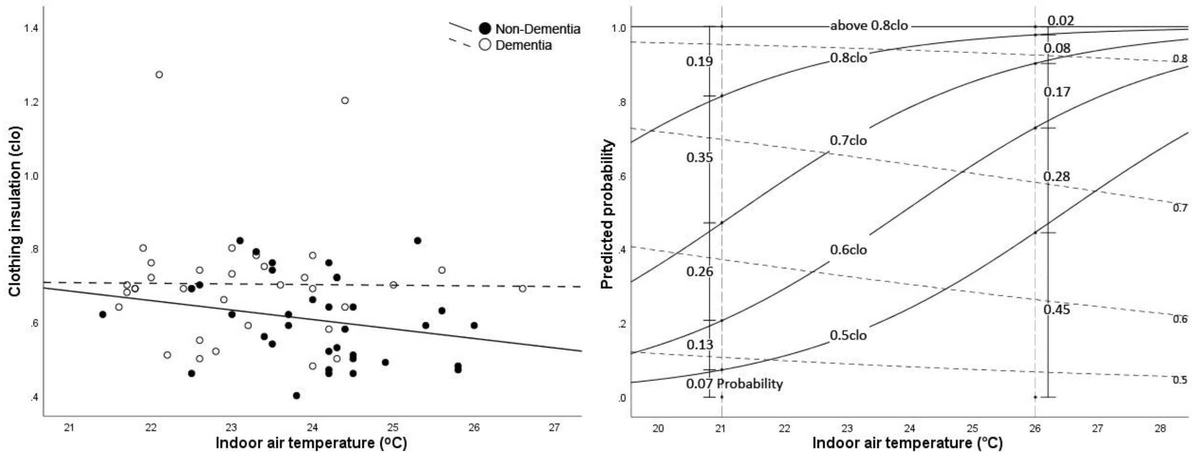
Figure 2. Seasonal indoor air temperature (a) and clothing insulation (b) for participants with and without dementia. *Each Notch indicates 25% from the median (thick solid line) and () is number of samples ($N_{dementia}$, $N_{non-dementia}$).

As care homes provide care for residents with and without dementia, the field survey data allows us to explore differences in personal and environmental factors between these two groups. Among the known factors affecting residents' thermal sensations, clothing is the only one which care home residents can voluntarily act upon. As shown in Figure 2 (b), participants with dementia tended to wear slightly thicker clothes than participants without dementia in both heating and summer periods with two extremity outliers, where the indoor temperature was lower than that of residents without dementia (Figure 2 (a)). Transition months were not compared. An independent-samples t-test was performed to compare the factors affecting thermal sensations between the two groups over a year. Table 2 shows that there was a statistically significant difference in air temperature and clothing insulation between the two groups.

Table 2. Outputs of Differences (T-test) in each of factors between participants with and without dementia over a year. (): Non-dementia

	N	Mean	St. Dev.	Sig.	Eta squared	Magnitude of difference
Indoor Temp (^{o}C)	34 (35)	23.15 (24.07)	1.21 (1.03)	.001	.149	large
RH (%)	34 (35)	49.40 (52.10)	6.37 (9.60)	.174	.027	small
Clothing (*clo*)	34 (35)	.70 (.60)	.16 (.12)	.005	.111	large

The selection of clothing can be considered an important voluntary action to maintain or to restore thermal comfort. We investigated the relationship between clothing insulation (*clo*) and indoor air temperature (^{o}C). Overall, as shown in Figure 3 (a), clothing was not linearly fitted with indoor temperature in all residents over a year, while residents without dementia were relatively more responsive to indoor temperature change than residents with dementia. We further analysed these data with a probabilistic approach using ordinal logistic regression. Given the sample sizes N=35 for Non-dementia and N=34 for Dementia, the predicted probability did not meet statistical significance. However, it reveals the differences in how the clothing selections by residents with or without dementia responded to the indoor temperatures. Figure 3(b) shows that the predicted clothing insulation probabilities for residents without dementia (solid lines) were inversely related to indoor temperature, as expected (i.e., higher temperature → lower *clo* with reasonable changes of probabilities accordingly). Furthermore, when indoor temperature is 21^{o}C (low in comparison with the annual mean of 24.07^{o}C), the clothing level with the highest predicted probability (at 0.35) is 0.7-0.8 *clo*, ("thicker" than the annual mean of 0.6 *clo*), while the thinnest *clo* (below 0.5) has the lowest probability, at 0.07. When indoor air temperature is 26^{o}C, (which is relatively high), the predicted probability of the thick *clo* (0.7-0.8) is reduced to 0.08 (from 0.35), while the probability of the thin *clo* (0.5) is increased to 0.45 (from 0.07). However, the converse is the case for residents with dementia.



(a) (b)

Figure 3. (a) Linear fit of Clothing insulation (*clo*) to indoor air temperature; (b) Fitted ordinal logistic model of *clo* probabilities with respect to indoor air temperature for non-dementia group. Dash line: people with dementia

The implication of a person with dementias' selection of clothing can be problematic for maintaining their thermal comfort considering the selection of clothing is the voluntary action to restore their thermal comfort. Outdoor mean temperature may be a more precise predictor on selection of *clo* [85]. Further study, and a significantly larger sample size, is required for this, perhaps including a survey of outdoor activities (physical exercise) in care homes.

4.2. Application of PMV to the care home residents

4.2.1. Probability of the estimated MET for thermal neutrality

Of the six predictors on PMV estimation, metabolic rate (MET) has been identified as the most sensitive variable [86]. We carried out a sensitivity analysis of PMV to MET, given the collected samples. A forward finite difference equation was used to calculate magnitude of change (sensitivity, S_j) of PMV by MET (0.1 MET): $S_j = (PMV_i - PMV_j)/(MET_i - MET_j)$ within the range of 0.7-2.0 MET. The proportion was determined by max S_j (10.8) and min (0.1), meaning the largest magnitude change of PMV is 1.08 PMV between 0.7 and 0.8 MET (Figure 4). It also shows that a high sensitivity occurred below 1.3 MET, and very high below 1 MET. This suggests that when applying PMV to assess thermal comfort of older people in care homes, who are inherently biased towards low physical activity levels, some care is needed in measuring (or estimating) MET. Indeed, we would argue that, with a progressively ageing global population, there is a need for new laboratory studies on metabolic rates with which to derive new, more applicable, predictive models.

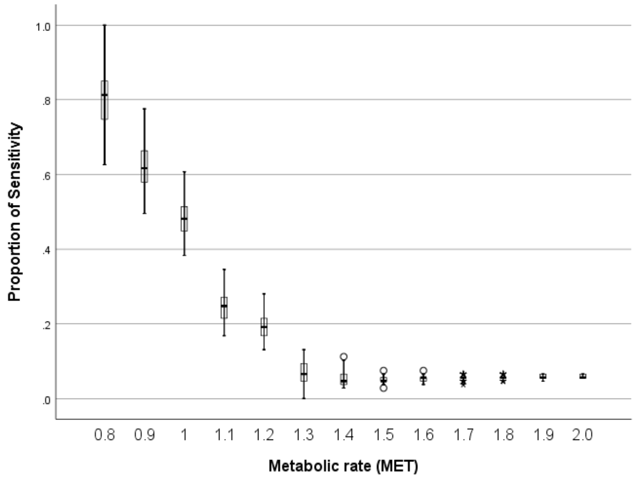
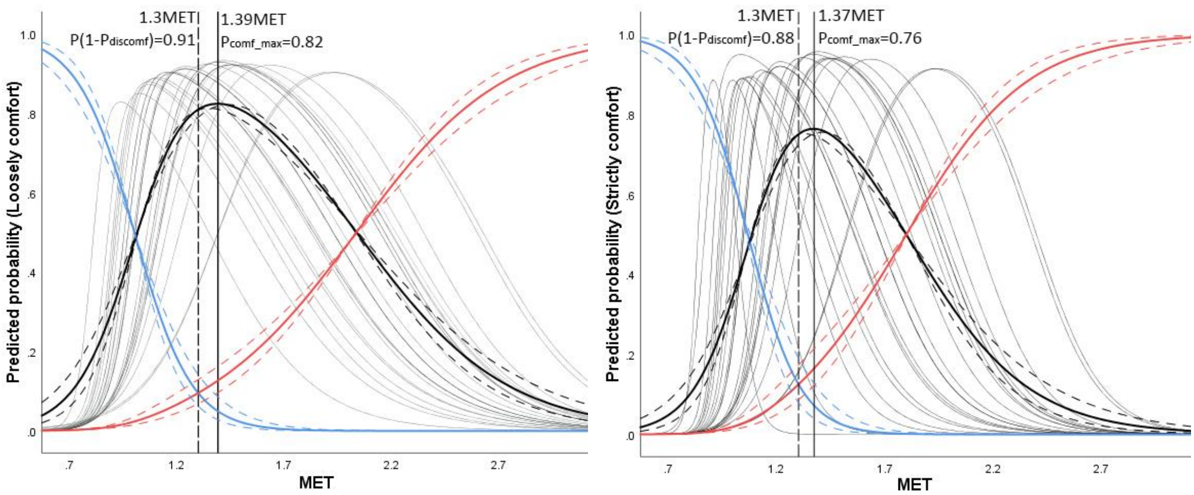


Figure 4. Sensitivity of the predicted mean vote (PMV) to metabolic rate (MET).

In the absence of measured MET, MET was estimated by investigating the relationship between actual thermal sensation vote (TSV) and the predicted mean vote (PMV), under the assumption that PMV, in principle, is applicable to care home residents. This is to investigate the diversity of personal metabolic rate under the assumption that PMV is applicable to older residents in care homes. Considering the uncertainty in the reliability of TSV received from participants with dementia, we used only samples from the non-dementia group with "neutral thermal sensation", which can be compared to "neutral" votes predicted by PMV. We used two bands of PMV for thermal neutrality centred to 0: $-1 \leq PMV \leq 1$ for "loosely comfortable", and $-0.5 \leq PMV \leq 0.5$ for "strictly comfortable". Given each participant's actual ambient indoor climate and clothing insulation datasets, a possible metabolic rate was initially calculated using the PMV calculator (CBE Thermal Comfort Tool ASHRAE-55, https://comfort.cbe.berkeley.edu/) according to each PMV threshold value (i.e., -1.2, -1.0, -0.5, -0.2, 0, 0.2, 0.5, 1.0, 1.2). Then, the probability of each participant's MET was estimated using multinomial logistic regression under a threefold thermal sensation: cool (below -0.5 PMV), neutral ($-0.5 \leq PMV \leq 0.5$), and warm (above 0.5) in the case of "Strictly comfortable".

Figure 5 shows the thermal neutrality probabilities fitted with the estimated MET of the non-dementia group. The estimated MET is largely distributed between 0.91 and 1.95 in both loosely and strictly comfortable cases, while it is centred between 1.3 and 1.39 MET by aggregation. However, considering the expected low MET of older sedentary people compared to an average young adult (about 1.2 MET), this result might be somewhat overestimated. This implies that the threshold of PMV (with its applicable range) for thermal neutrality might be biased towards negative PMV values.



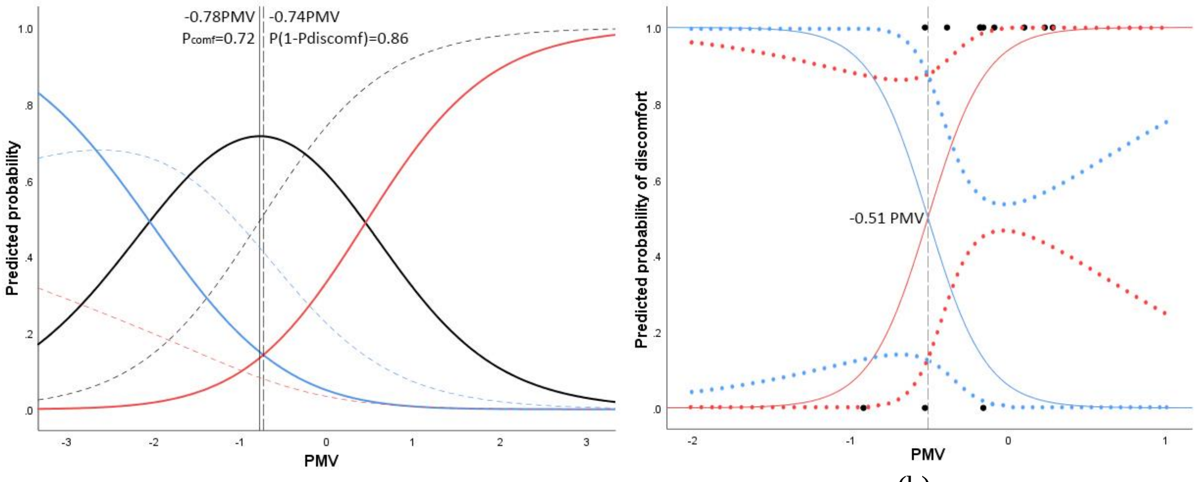
(a) Loosely comfortable (b) Strictly comfortable

Figure 5. Fitted individual thermal neutrality probabilities with respect to MET in the non-dementia. *Solid line: aggregated thermal neutrality (black), cool (blue) and warm (red) discomfort, and their 95% CI (dash line). The MET value at P_{comf_max} indicates the comfort-maximising metabolic rate.

4.2.2. Possible PMV thresholds for thermal comfort in care homes

To identify a possible threshold of PMV for thermal comfort of care home residents, a first estimation of personal MET using only the age and gender data available from the field survey was used, with other inputs taken to be the same as an "average adult" of 30 years old. Based on the estimated MET (plausible range of sedentary activities, 1.07 ± 0.06), each subject's PMV was calculated. Then, using their actual thermal sensation vote, a probabilistic model was generated using multinomial logistic regression. Samples were again divided into two groups (dementia and non-dementia), due to the uncertainty in thermal responses from people with dementia.

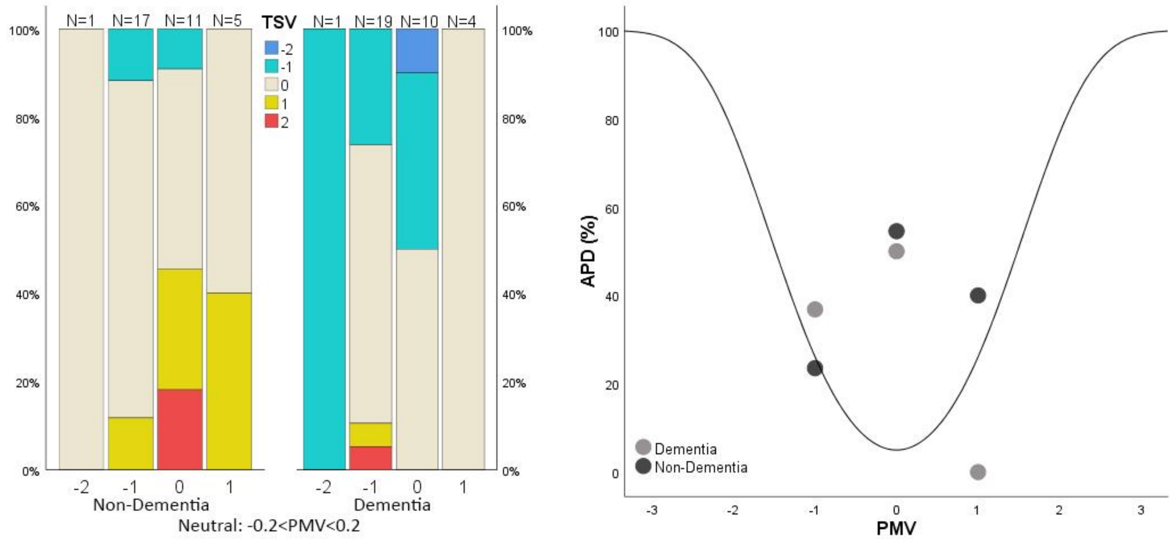
Figure 6 (a) shows that the threshold of PMV for comfort lies at around -0.76, which is biased to "minus" from 0, given the estimated MET. The biased PMV (to minus) for thermal comfort was also confirmed from the relationship between TSV and PMV in Figure 7 where a relatively large proportion of thermal neutrality in TSV is placed at -1 PMV scale. However, for the dementia group, the thermally neutral probability did not follow the normal curve. This may result from either the wrong assumptions in estimating the MET or the unreliability of the returned TSV. If the body sizes (weight and height) of the dementia group are not substantially different from the non-dementia group, the thermal responses from residents with dementia are not reliable for PMV to be applicable. Furthermore, some relatively odd discomfort votes from the dementia group can be seen in Figure 7.



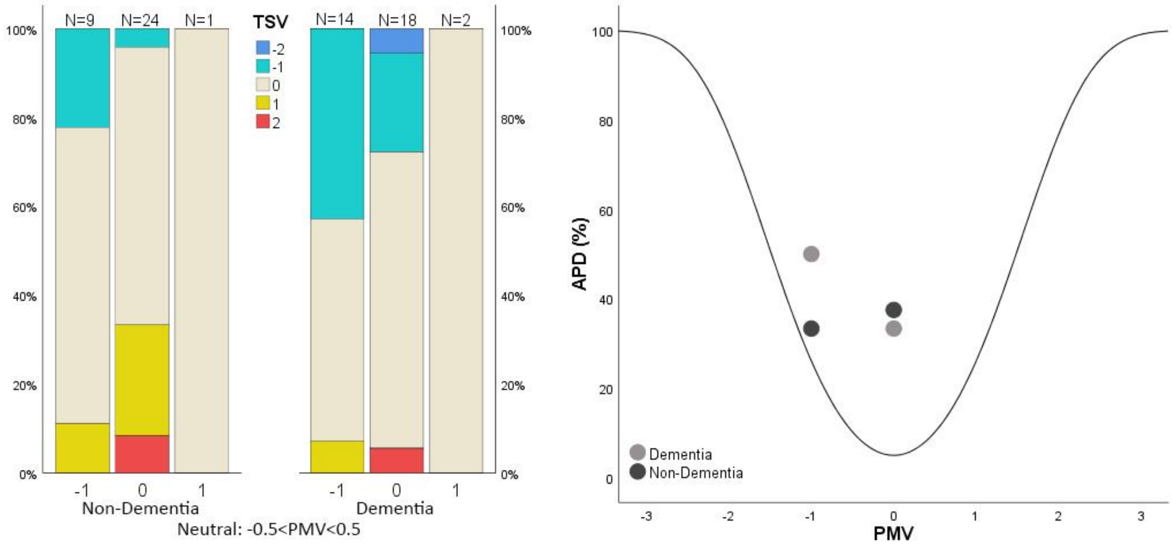
(a) (b)

Figure 6. (a) Probabilities of thermal neutrality (black line) and discomfort (blue for cool discomfort and red for warm discomfort) fitted with the PMV of the dementia (dash line) and non-dementia groups (solid line); (b) Binary logistic model of warm (red) and cool (blue) discomfort to estimated PMV of the non-dementia group with observed TSV (0=cool discomfort; 1=warm discomfort). *Dash line: their 95% CI band of the likely asymmetric location of the true parameter.

To confirm if the PMV is biased to minus for comfort, we carried out a binary (warm and cool discomfort) logistic regression for the non-dementia group. Figure 6 (b) shows that the threshold of PMV for thermal comfort was identified at -0.51 of PMV where both warm and cool discomfort curves are crossed at $P(1-P_{warm})(1-P_{cool})=0.5$. Here the model reliability is inconclusive as seen in the 95% of confidence interval, which is largely overfitted due to a likely lack of TSV samples reporting discomfort. However, collecting discomfort data may be challenging in field studies of existing care homes because the corresponding conditions may endanger residents' health. Also, the PMV-based approach may need to consider the relatively thermally homogenous heating season in case of the UK. In this study, the sample size of the non-dementia group for the heating season is only 9: cool (N=1); neutral (6); warm (2).



(a) Neutral: -0.2<PMV<0.2



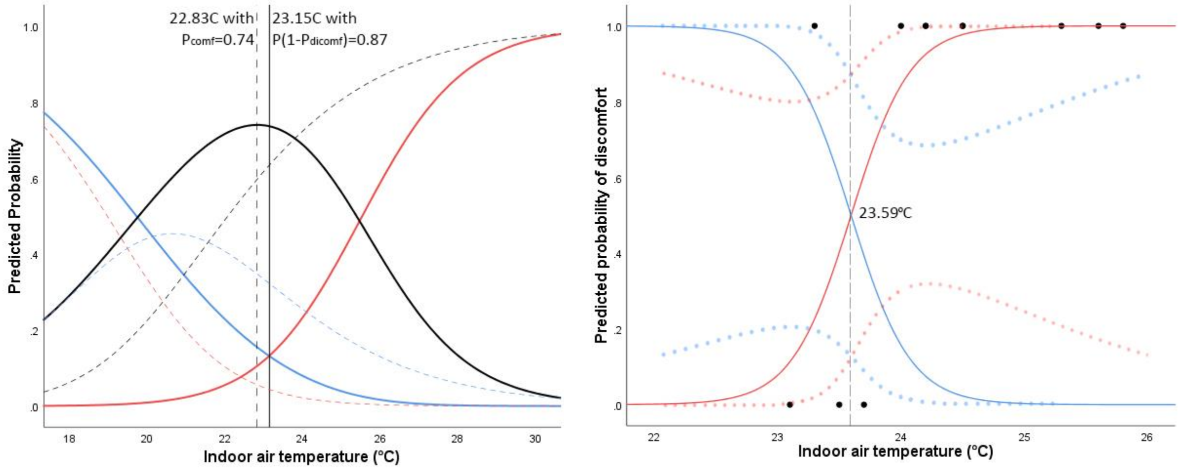
(b) Neutral: -0.5<PMV<0.5

Figure 7. Binned actual thermal sensation vote (TSV) with respect to the interpreted PMV thermal scale and PMV-APD (actual percentage of discomfort) relationship compared to the Fanger's PMV-PPD model (solid line) between the dementia and non-dementia. Cases (N<4) are excluded in PMV-APD.

4.3. Adaptive approach to thresholds of indoor air temperature for thermal comfort in care home residents

As seen in Figure 3 (b), the residents without dementia seem to take actions to maintain their thermal comfort or restore thermal discomfort by clothing selection in response to the indoor air temperature. Also, according to the thermal preference vote, about 80% (N=28/35) of the non-dementia group did not want to change their existing indoor thermal conditions. Thus, we examined an adaptive comfort approach using probabilistic modelling to deduce thermal comfort zones in the care homes using multinomial logistic regression on thermal sensation with respect to indoor air temperature. Owing to the small sample size, we reclassify the 7-point TSV into three categories: cool (TSV≤-1), neutral (0), and warm (TSV≥+1). Also, considering that it could be difficult for the participants to determine their actual thermal sensations near to neutral, we also used a binary logistic regression using only the TSV reporting cool and warm discomfort. Figure 8 shows the outputs, from which comfort zones can be determined between 22.83°C and 23.59°C with max probabilities, where $P_{comf,\_max}$ = 0.74 and P(1-P_{cool})(1-P_{warm}) = 0.87 in multinominal, and P(1-P_{cool})(1-P_{warm}) = 0.5 in binary logistic regression.

As this approach assumes voluntary adaptive actions to maintain thermal comfort, its applicability may be limited to residents who do not have dementia. This was confirmed in the comfort probability model fitted to the dementia group (shown in the dash lines in Figure 8 (a)). However, based on the findings of temperature in Figure 8 and clothing insulation responding to indoor temperature in Figure 3 (b), the thresholds derived from the non-dementia group through the adaptive method may be applicable to provision of assistive care for residents with dementia.



(a) (b)

Figure 8. (a) Probabilities of thermal neutrality (black line) and discomfort (blue for cool discomfort and red for warm discomfort) fitted with indoor air temperature for the non-dementia group using multinomial logistic regression; and (b) binary logistic regression with observed TSV (0=cool; 1=warm discomfort). * Dash line: Dementia group in (a) and 95% CI in (b).

4.4. Modelling thermal comfort based on IRT imaging of extremities

4.4.1. IRT (ΔT_1 and ΔT_2) threshold for thermal comfort in the care homes

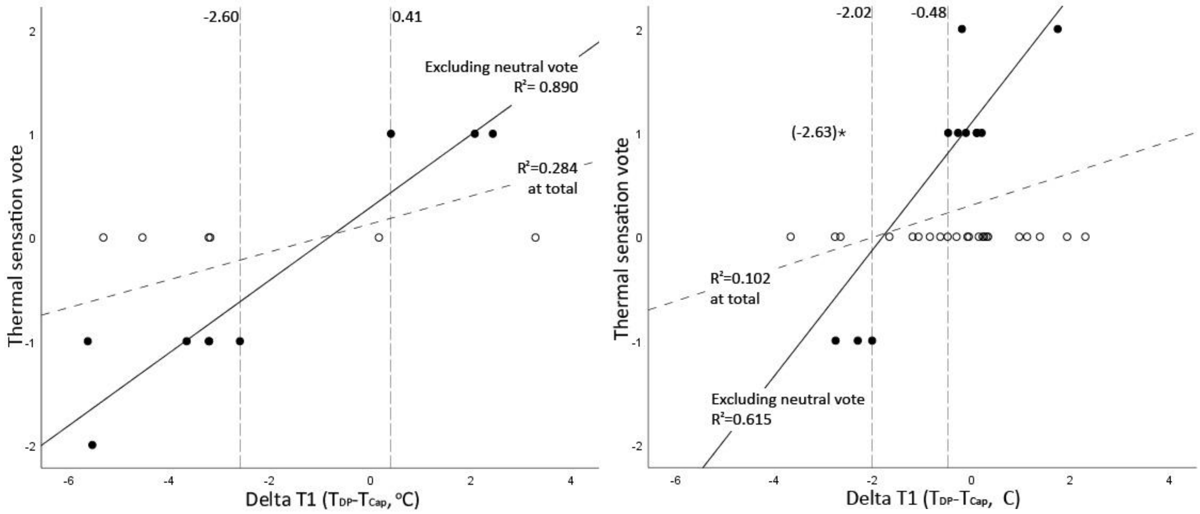
We first performed a relational analysis between the infrared thermography (IRT) data of a non-dominant hand and actual thermal sensation vote (TSV) to investigate how the IRT measurements can be an indicator of thermal comfort or discomfort. As described in section 3.2.3, we focussed on the temperature differences between the temperature of distal phalange (T_{Dp}) and capitate bones (T_{Cap}) and distal humerus (T_{Dh}) from the physiological point of view. Hence, $\Delta T_1 = T_{Dp} - T_{Cap}$ and $\Delta T_2 = T_{Dp} - T_{Dh}$. Also, TSV' was defined as the *votes for thermal discomfort* by excluding the "neutral" votes in the original TSV dataset. Spearman correlation was used as TSV is categorical. Table 3 shows the outputs.

Table 3. Spearman correlation coefficients between infrared thermography (IRT) data and actual thermal sensation vote (TSV) in both young adults and older people. TSV': thermal discomfort where excluding samples of neutral responses in TSV. ** Sig. < .01 and * Sig. < .05

		Young Adults		Care home residents			
				Dementia		Non-Dementia	
		TSV	TSV'	TSV	TSV'	TSV	TSV'
ΔT_1	Spearman-C	.463	.839**	-.068	-.119	.247	.667*
($T_{Dp} - T_{Cap}$)	Sig.	.061	.005	.707	.712	.159	.018
	N	17	9	33	12	34	12
ΔT_2	Spearman-C	.488*	.839**	.076	.129	.290	.631*
($T_{Dp} - T_{Dh}$)	Sig.	.047	.005	.675	.691	.096	.028
	N	17	9	33	12	34	12

In the case of the young adults, Spearman correlation coefficients between Δ values and TSV (and TSV', thermal discomfort) show that there was a much stronger relationship in TSV' than in TSV, with the correlation being significant at the .01 level. This stronger correlation also occurred in the non-dementia group. Furthermore, ΔT_1 was slightly more influential than ΔT_2 on TSV'. This suggests that ΔT_1 can be a potential indictor in determining thermal discomfort (cool and warm) in both age groups.

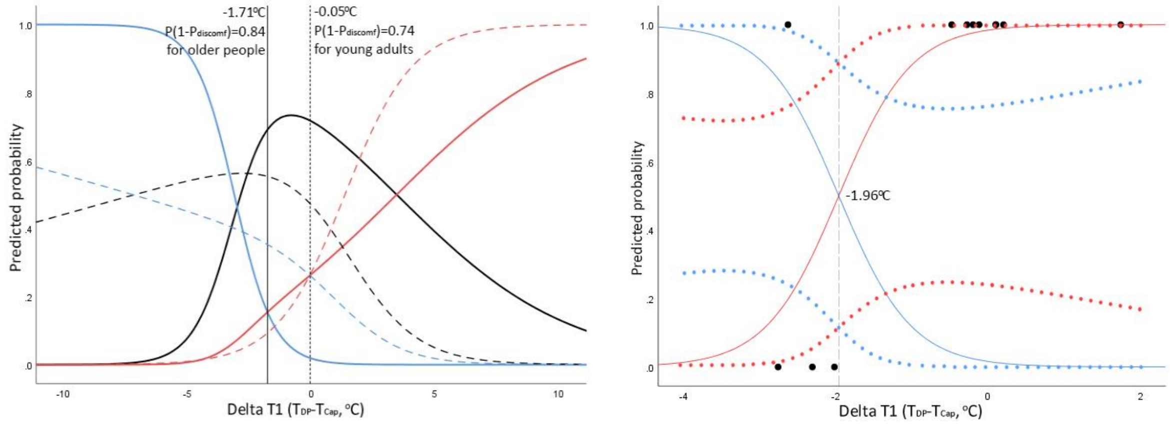
To confirm this, we carried out further analyses via thermal comfort modelling of the young group and the older group separately. However, in the dementia group, the ΔT values were not correlated with either TSV or TSV'. Here, if ΔT_1 is considered a potential indicator of residents' thermal sensations, there may be a question regarding the reliability of the TSV responses from the dementia group. We therefore propose to extrapolate the mapping from ΔT values to TSV from the non-dementia group to the dementia group, this being a reasonable compromise between reliability and practicality. Thus, only the IRT data from the non-dementia group was used in modelling thermal comfort. Figure 9 shows how ΔT_1 are related to participants' actual thermal sensations.



(a) (b)

Figure 9. Linear relationship between ΔT_1 ($T_{Dp} - T_{Cap}$, °C) and TSV in young adults (a) and in non-dementia care home residents (b).

As seen in Figure 9 (both young and older people), the responses of thermal neutrality were widely scattered through the whole range of ΔT_1. When excluding the neutral thermal sensations from all samples, discomfort datasets show a better linear fit between them. It follows that usage of discomfort data can be effective when the collection of large samples may prove difficult, with cool and warm votes being more weighted than neutral votes. To explore this further, we carried out two types of probabilistic modelling to identify possible thresholds of ΔT_1 for thermal comfort zones: multinomial and binary (cool and warm discomfort) logistic regression.



(a) (b)

Figure 10. (a) Fitted thermal neutrality (black line) and discomfort (blue for cool discomfort and red for warm discomfort) probabilities with respect to ΔT_1 by using multinomial logistic regression for the non-dementia group (Dash line: young adults). (b) Fitted binary (cool and warm) discomfort model on ΔT_1 for the non-dementia group with observed TSV (0=cool; 1=warm, Dash line: 95% CI).

In Figure 9, the discomfort samples are biased to warm (in older people) and cool (in young adults). The fitted thermally neutral probabilistic model is also biased accordingly as shown in Figure 10 (a). To identify the threshold of ΔT_1 for thermal neutrality, the cross-point of discomfort was used: P(1-P_{cool})(1-P_{warm}). In the case of young adults, the threshold for thermal neutrality (neither cool nor warm) was found to be near to 0 (-0.05 °C of ΔT_1) with P(1-P_{cool})(1-P_{warm})=0.74, while that of older people was -1.71 °C of ΔT_1 with P(1-P_{cool})(1-P_{warm})=0.84. Similarly, this threshold of older people was determined using the binary approach in Figure 10 (b): ΔT_1 = -1.96 °C with P(1-P_{cool})(1-P_{warm}) = 0.5. However, as indicated by the 95% CI, the determination of a possible range of ΔT_1 for thermal comfort is limited by the small sample size. Notably, the young adult's threshold of thermal neutrality met the theoretically ideal point, ΔT_1 = 0, where T_{Dp} is equal to T_{Cap}; whereas older people are associated with a lower value.

4.4.2. Factors in IRT (ΔT_1)

We investigated which factors are dominant in determining ΔT_1 using Pearson correlations (Table 4). Firstly, common to both age groups, ΔT_1 is more strongly correlated with T_{Dp} than with T_{Cap}. This confirms what is physiologically expected: fingertips (T_{Dp}) as radiator organs. Secondly, there were different correlation coefficients found in each of the variables in the two age groups. In the case of young adults, indoor air temperature (+), clothing insulation (+) and age (-) were strongly correlated with ΔT_1, while core body temperature (+) and clothing insulation (-) had an influence on ΔT_1 at a level of sig. < .01 in older people.

Another noteworthy observation is that clothing insulation in care home residents is negatively correlated with ΔT_1, in contrast to that observed in young adults. However, as we know from the field survey that the prevailing indoor thermal condition (air temperature) of the dementia group was lower than the non-dementia group (also the opposite in clothing insulation, see Figure 2), the negative influence of clothing on ΔT_1 was clearly found only in the dementia group (Table 4). This implies that under a (relatively) low temperature condition, thicker clothing may not always lead to an increase of hand temperature. Furthermore, the effect of frailty (clinical score 0 to 6: 0, very fit; 6, severely frail) on ΔT_1 was found not statistically significant.

Table 4. Pearson correlation coefficients between infrared thermography (IRT) ΔT_1 ($T_{Dp} - T_{Cap}$, °C) and several factors in both young adults and care home residents. () is Sig. ** Sig. < .01 and * Sig. < .05. For frailty, Spearman correlation.

		T_{Dp}, (°C)	T_{Cap}, (°C)	Core Body Temp, (°C)	Indoor air temp, (°C)	Clothing (clo)	Age (years)	Frailty
Young adults	N=17	.916**	.324	.086	.833**	.724**	-.611**	-
		(<.001)	(.205)	(.744)	(<.001)	(.001)	(.009)	-
Older total	N=67	.862**	.411**	.349**	.150	-.339**	-.166	-.121
		(<.001)	(<.001)	(.004)	(.222)	(.005)	(.177)	(.327)
Non-dementia	N=34	.816**	.326*	.249	.037	-.059	-.357*	-.080
		(<.001)	(.033)	(.155)	(.832)	(.735)	(.035)	(.648)
Dementia	N=33	.875**	.452**	.303	-.011	-.363*	-.046	.004
		(<.001)	(.008)	(.086)	(.953)	(.038)	(.798)	(.983)

Table 5. Coefficients of multiple regression model for both young adults and older people and their error statistics: the observed and predicted mean ± 95% confidence interval for mean (°C), mean absolute error (MAE), root mean squared error (RMSE).

	Dependent	Independent	*B*	Std. Error	Beta	Sig.
R^2=.700	ΔT_1 (°C)	(Constant)	-48.988	17.381		.015
p=.001	Young adults	Air temperature (°C)	2.045	.818	.814	.027
N=17		Clothing (*Clo*)	2.259	5.959	.104	.711
		Age (*years*)	.045	.124	.087	.723
R^2=.209	ΔT_1 (°C)	(Constant)	-43.942	17.251		.013
p=.001	Older people	Core body temp (°C)	1.228	.465	.298	.010
N=67		Clothing (*Clo*)	-3.332	1.256	-.299	.010

Error Statistics		Mean. Pred.	Mean. Obs.	MAE (°C)	RMSE (°C)
	Young adults	-2.73 ± 1.42	-2.73 ± 1.70	1.58	1.76
	Older people	-1.02 ± 0.19	-1.02 ± 0.41	1.19	1.47

In the multiple linear regression analysis, the variables were selected at a level of Sig. < 0.01 (Table 4). Considering ΔT_1 and other variables, which are the objective and continuous measurements, all samples (N=17 for young adults and N=67 for older people) were used in the analysis. Table 5 shows the outputs of multiple linear regression analysis and its error statistics. The indoor air temperature (+) was identified as the most influential factor on ΔT_1 (°C) in young adults, but other variables did not meet statistical significance owing to the small sample (N=17). In older people however, core body temperature (+) and clothing insulation (-) had a similar influence on ΔT_1 at a level of Sig.<0.05. Like the correlational study, the effect of clothing insulation on ΔT_1 was negative, which might be derived from those residents with dementia (see Table 4). By contrast to young adults, core body temperature can play a key role in ΔT_1 for older people. This implies that under the controlled indoor thermal conditions of care homes, the interplay between physical activity, metabolic heat production and core body temperature can be reflected in cutaneous blood flow to fingertips (radiator organs), a visible (via IRT) reflection of the distribution of heat at the extremities and a crucial indicator of thermal comfort in older people.

Given the coefficients of the multiple regression model, we further evaluated model reliability. As the sample size is not sufficient to validate with other tests, only error statistics were examined within the modelled sample. Owing to the different correlated predictors and strengths in the correlation study, cross-validation between age groups was not considered either. Finally, following Haldi and Robinson [85], evaluation of model reliability in thermal comfort modelling can be performed by assessing the proportion of correctly classified thermal sensations through comparison between actual TSV and the thermal sensations predicted by ΔT_1 derived from the regression model. However, as we only have identified the threshold of ΔT_1 for thermal comfort in both age groups (-0.05°C for young adults; -1.96°C or -1.71°C for older people), the reliability of thermal comfort modelling based on IRT imaging of extremities should be evaluated in further research.

5. Discussion and Conclusions

In this paper, we have introduced a novel probabilistic technique for thermal comfort modelling which accounts for individual distributions of thermal sensations potentially derived from personal expectations and biological ageing compounded with residents' underlying health conditions. Applying it to the evaluation of heat balance, adaptive comfort, and thermographic methods to care home setting, this pilot study aimed to inform the research design of a large fieldwork campaign, to develop a rigorous evidence base to support thermal design and control for the care home sector. The data underpinning all three should be consolidated, with a view to determining which of them can be most reliably and practicably employed to satisfy the dual objectives of energy and discomfort minimisation. Whilst these models provide valuable insight to the complex problem of provision of thermal comfort to older people, the utility of employing these models in day-to-day residential care has yet to be investigated for possible incorporation into care guidelines.

Applicability of PMV in care homes: In the absence of measured energy expenditure and thus metabolic rate, PMV may be applicable to care homes in principle under an assumed plausible MET range (1.07 ± 0.06) of sedentary activities, where the body sizes of residents are not significantly different from average young adults and the threshold of comfort PMV lies at around -0.75 to -0.51. However, the applicability of this stationary model to dynamic everyday life in care homes and the level of frailty of the older residents is challenging in terms of data requirements and sensitivity on PMV estimation. PMV is particularly sensitive to air speed, clothing insulation and MET. Thus, inaccurate assumptions can undermine the utility of PMV-based thermal comfort assessment [54]. Havenith et al. [28] reported that clothing insulation (*clo*) and MET (below 2 MET in particular) must be carefully considered in PMV assessment. However, real life measurements of metabolic rate, using indirect calorimetry, are challenging and would require a feasibility study for this very aged group. Also, current equations of resting metabolic rate should be evaluated for their reliability [87].

Adaptive methods to deduce thermal comfort temperature: The failure to account for feedback of behavioural adaptations can undermine the applicability of a stationary PMV model to transient environments. As discussed by Haldi and Robinson [66], conventional comfort criteria account for comfort assessment and adaptive actions (and personal expectations) separately, despite these being intrinsically interdependent. This study suggests that Adaptive Comfort appears to be well suited and can also consider feedbacks from adaptive actions, but this requires a significant pool of data. Based on the field survey, the threshold of comfort temperature is determined between 22.83°C and 23.60°C using measurements obtained from patients without dementia only. This finding would be comparable to the indoor minimal risk temperature for thermal-related health effects recommended from the WHO guideline [88]: for instance, 22-23°C for heat-related conditions in the United Kingdom. Further studies are required to establish guidelines for older people under cold-related conditions.

Infrared thermographic imaging of the skin temperature of the non-dominant hand: The difference in skin temperatures between distal phalange and capitate bones can be an indicator of thermal comfort for care home residents who may have difficulties in taking timely adaptive actions, where the threshold for thermal neutrality is between -1.96°C and -1.71°C ΔT_1, which is lower than that of young adults (near to 0°C ΔT_1). If these measurements can be practically deployed, the IRT based approach would be valuable for carers to make timely assessments and to take adequate actions to help the residents who are unable to communicate appropriately to maintain or restore thermal comfort.

Finally, based on the findings of this study, the following measures can be considered to mitigate potential thermal discomfort for older residents living in residential care where the usual activity is of a sedentary nature:

- Indoor air temperature between 22.83°C and 23.60°C as a comfortable range over a year.
- *Clo* of 0.6 ± 0.12 as derived from the non-dementia group, but this should be updated through further modelling of clothing selection corresponding to both outdoor and indoor temperature.

6. Implications and Future Studies

This pilot study shows that probabilistic thermal comfort modelling technique is pertinent to the care home setting, but doing so effectively in practice would require a substantially larger dataset to substantiate the model reliability. The sample size of logistic models in medical studies can typically be examined by an Event per Variable criterion (EPV), which is determined by the ratio of the number of events divided by the number of predictor variables (strictly, degree of freedom [89]). Although this can vary depending on the strength of association between covariates and outcomes, such as the estimated maximum likelihood of odd ratio [90, 91], EPV ≥ 10 can be considered the minimum in the binary model with a single predictor [92, 93], or EPV ≥ 50 in case of stepwise predictor selection with a significance level of 0.05 [94]. This suggests samples of at least N=50 for each discomfort event (cool and warm). Sampling must also be carefully performed to effectively represent the distinct ‘populations’ of care home residents. For instance, this study divided samples into people with and without dementia, and found that all three approaches were limited by the samples collected from subjects with dementia (compounded by the likelihood that votes from this group are uncertain).

In further studies, it would be beneficial to collaborate with carers in collecting samples from care home residents during their everyday life. It is of a particular research interest to acquire survey data for both cool and warm conditions, and for sufficiently large sample to identify statistically reliable thresholds of thermal comfort. This is because participants (even young adults) have difficulties in defining their actual thermal sensations near thermal neutrality [95]. Considering the decreased thermal sensitivity and perception, it will be more difficult for older residents in care homes to determine and communicate reliably their actual thermal sensation near to neutral.

To place the adaptive comfort model into practice, the availability of individual adaptive behaviours and corresponding feedbacks must be effectively examined, even under the relatively homogeneous indoor thermal environments. Observed examples of adaptive behaviours of older people [15, 96, 97] include adjusting their location, activity level, posture, clothing, and use of doors, curtains and blinds and the consumption of drinks.

Given that care homes (and other relevant facilities) have limited potential to provide personalised indoor climates to residents, it would seem particularly important to account for the combined effect of biological ageing and personal health conditions together with available adaptive actions and their impacts on under- or over-heating risks, to avoid adverse health effects. Even in the UK context, care homes can be exposed to potential overheating risk during the summer period [98], where indoor cooling largely relies on natural ventilation. It would also be useful to better understand the extent to which setpoint temperatures (for heating) can be lowered by compensating with higher clothing level (or with other possible operational aids) whilst ensuring localised comfort is not compromised, to save energy and reduce carbon emission.

Finally, this pilot study has only shown a 'learning' in understanding the conditions of the built environment that has been little studied for those being cared. Further research is required to drive forward our understanding of thermal comfort and ways of achieving comfort for those at risk in the care home environment, and thus to support the evidence-based formulation of guidelines for the indoor environmental management of care homes.

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References

[1] United Nation, World Population Ageing 2019: Highlights (ST/ESA/SER.A/430). Official, 2019.

[2] Office for National Statistics, Overview of the UK Population: November 2018, Off. Natl. Stat. (2018).

[3] C.& M. Authority, Care homes market study: summary of final report, 2017. https://www.gov.uk/government/publications/care-homes-market-study-summary-of-final-report.

[4] G. Newell, M.J. Marzuki, The increasing importance of UK healthcare property as an alternate property sector, J. Prop. Invest. Financ. 36 (2018) 466–478. https://doi.org/10.1108/JPIF-03-2018-0019.

[5] A. Flynn, C. McGreevy, E.C. Mulkerrin, Why do older patients die in a heatwave?, QJM - Mon. J. Assoc. Physicians. 98 (2005) 227–229. https://doi.org/10.1093/qjmed/hci025.

[6] E. Grundy, Ageing and vulnerable elderly people: European perspectives, Ageing Soc. 26 (2006) 105–134. https://doi.org/10.1017/S0144686X05004484.

[7] N.D. Thomas, H. Soliman, Preventable tragedies: Heat disaster and the elderly, J. Gerontol. Soc. Work. 38 (2003) 53–66. https://doi.org/10.1300/J083v38n04_06.

[8] S. Hajat, T. Kosatky, Heat-related mortality: A review and exploration of heterogeneity, J. Epidemiol. Community Health. 64 (2010) 753–760. https://doi.org/10.1136/jech.2009.087999.

[9] R.S. Kovats, S. Hajat, Heat stress and public health: A critical review, in: Annu. Rev. Public Health, 2008: pp. 41–55. https://doi.org/10.1146/annurev.publhealth.29.020907.090843.

[10] A. Fouillet, G. Rey, F. Laurent, G. Pavillon, S. Bellec, C. Guihenneuc-Jouyaux, J. Clavel, E. Jougla, D. Hémon, Excess mortality related to the August 2003 heat wave in France, Int. Arch. Occup. Environ. Health. 80 (2006) 16–24. https://doi.org/10.1007/s00420-006-0089-4.

[11] S. Hajat, R.S. Kovats, K. Lachowycz, Heat-related and cold-related deaths in England and Wales: Who is at risk?, Occup. Environ. Med. 64 (2007) 93–100. https://doi.org/10.1136/oem.2006.029017.

[12] G. Havenith, Temperature regulation and technology, Gerontechnology. 1 (2001) 41–49. https://doi.org/10.4017/gt.2001.01.01.004.00.

[13] B.J. Holtzclaw, Chapter 14. Environmental safety and security, in: A.S.L. (Eds. . P. Ebersole, P. Hess (Ed.), Towar. Heal. Aging (6th Ed.), 6th ed., Mosby, St. Louis, Mo, USA, 2004: pp. 417–430.

[14] R. Hitchings, G. Waitt, K. Roggeveen, C. Chisholm, Winter cold in a summer place: Perceived norms of seasonal adaptation and cultures of home heating in Australia, Energy Res. Soc. Sci. 8 (2015) 162–172. https://doi.org/10.1016/j.erss.2015.05.007.

[15] J. van Hoof, L. Schellen, V. Soebarto, J.K.W. Wong, J.K. Kazak, Ten questions concerning thermal comfort and ageing, Build. Environ. 120 (2017) 123–133. https://doi.org/10.1016/j.buildenv.2017.05.008.

[16] J. van Hoof, H.S.M. Kort, J.L.M. Hensen, M.S.H. Duijnstee, P.G.S. Rutten, Thermal comfort and the integrated design of homes for older people with dementia, Build. Environ. 45 (2010) 358–370. https://doi.org/10.1016/j.buildenv.2009.06.013.

[17] L.D. Hill, L.H. Webb, K.C. Parsons, Carers' views of the thermal comfort requirements of people with physical disabilities, in: Proc. XIVth Trienn. Congr. Int. Ergon. Assoc. 44th Annu. Meet. Hum. Factors Ergon. Assoc. 'Ergonomics New Millenn., 2000: pp. 716–719. https://doi.org/10.1177/154193120004402885.

[18] H. Verbeek, E. Van Rossum, S.M.G. Zwakhalen, G.I.J.M. Kempen, J.P.H. Hamers, Small, homelike care environments for older people with dementia: A literature review, Int. Psychogeriatrics. 21 (2009) 252–264. https://doi.org/10.1017/S104161020800820X.

[19] T. O'Neill, C. Jinks, A. Squire, "Heating is more important than food": Older women's perceptions of fuel poverty, J. Hous. Elderly. 20 (2006) 95–108. https://doi.org/10.1300/J081v20n03_07.

[20] P. Howden-Chapmam, Housing standards: A glossary of housing and health, J. Epidemiol. Community Health. 58 (2004) 162–168. https://doi.org/10.1136/jech.2003.011569.

[21] C. Childs, J. Elliott, K. Khatab, S. Hampshaw, S. Fowler-Davis, J.R. Willmott, A. Ali, Thermal sensation in older people with and without dementia living in residential care: New assessment approaches to thermal comfort using infrared thermography, Int. J. Environ. Res. Public Health. 17 (2020) 6932. https://doi.org/10.3390/ijerph17186932.

[22] ISO, ISO 7730: Ergonomics of the thermal environment Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, ISO 7730; ISO Stand. Geneva, Switz. (2005).

[23] ASHRAE, Thermal Environmental Conditions for Human Occupancy, ANSI/ASHRAE Stand. 55-2004. 2004 (2004).

[24] V. Soebarto, H. Zhang, S. Schiavon, A thermal comfort environmental chamber study of older and younger people, Build. Environ. 155 (2019) 1–14. https://doi.org/10.1016/j.buildenv.2019.03.032.

[25] Y. Jiao, H. Yu, Y. Yu, Z. Wang, Q. Wei, Adaptive thermal comfort models for homes for older people in Shanghai, China, Energy Build. 215 (2020). https://doi.org/10.1016/j.enbuild.2020.109918.

[26] A. Mendes, C. Pereira, D. Mendes, L. Aguiar, P. Neves, S. Silva, S. Batterman, J.P. Teixeira, Indoor air quality and thermal comfort - Results of a pilot study in elderly care centers in portugal, J. Toxicol. Environ. Heal. - Part A Curr. Issues. 76 (2013) 333–344. https://doi.org/10.1080/15287394.2013.757213.

[27] A. Mendes, A.L. Papoila, P. Carreiro-Martins, L. Aguiar, S. Bonassi, I. Caires, T. Palmeiro, Á.S. Ribeiro, P. Neves, C. Pereira, A. Botelho, N. Neuparth, J.P. Teixeira, The Influence of Thermal Comfort on the Quality of Life of Nursing Home Residents, J. Toxicol. Environ. Heal. - Part A Curr. Issues. 80 (2017) 729–739. https://doi.org/10.1080/15287394.2017.1286929.

[28] G. Havenith, I. Holmér, K. Parsons, Personal factors in thermal comfort assessment: Clothing properties and metabolic heat production, in: Energy Build., 2002: pp. 581–591. https://doi.org/10.1016/S0378-7788(02)00008-7.

[29] National Health Service (NHS), Care homes, (2019). https://www.nhs.uk/conditions/social-care-and-support-guide/care-services-equipment-and-care-homes/care-homes/ (accessed October 28, 2021).

[30] World Health Organization (WHO), World report on ageing and health, 2015. https://apps.who.int/iris/handle/10665/186463.

[31] T.B.L. Kirkwood, A systematic look at an old problem, Nature. 451 (2008) 644–647. https://doi.org/10.1038/451644a.

[32] C.J. Steves, T.D. Spector, S.H.D. Jackson, Ageing, genes, environment and epigenetics: What twin studies tell us now, and in the future, Age Ageing. 41 (2012) 581–586. https://doi.org/10.1093/ageing/afs097.

[33] S. Vasto, G. Scapagnini, M. Bulati, G. Candore, L. Castiglia, G. Colonna-Romano, D. Lio, D.

Nuzzo, M. Pellicano, C. Rizzo, N. Ferrara, C. Caruso, Biomarkes of aging, Front. Biosci. - Sch. 2 S (2010) 392–402. https://doi.org/10.2741/s72.

[34] S. Guergova, A. Dufour, Thermal sensitivity in the elderly: A review, Ageing Res. Rev. 10 (2011) 80–92. https://doi.org/10.1016/j.arr.2010.04.009.

[35] M. Cleary, T. Raeburn, S. West, C. Childs, The environmental temperature of the residential care home: Role in thermal comfort and mental health?, Contemp. Nurse. (2019). https://doi.org/10.1080/10376178.2019.1583068.

[36] L. Schellen, W.D. van Marken Lichtenbelt, M.G.L.C. Loomans, J. Toftum, M.H. de Wit, Differences between young adults and elderly in thermal comfort, productivity, and thermal physiology in response to a moderate temperature drift and a steady-state condition, Indoor Air. 20 (2010) 273–283. https://doi.org/10.1111/j.1600-0668.2010.00657.x.

[37] N. Hashiguchi, Y. Tochihara, T. Ohnaka, C. Tsuchida, T. Otsuki, Physiological and subjective responses in the elderly when using floor heating and air conditioning systems, J. Physiol. Anthropol. Appl. Human Sci. 23 (2004) 205–213. https://doi.org/10.2114/jpa.23.205.

[38] D.W. DeGroot, W.L. Kenney, Impaired defense of core temperature in aged humans during mild cold stress, Am. J. Physiol. - Regul. Integr. Comp. Physiol. 292 (2007). https://doi.org/10.1152/ajpregu.00074.2006.

[39] J. Van Hoof, J.L.M. Hensen, Thermal comfort and older adults, Gerontechnology. 4 (2006) 223–228. https://doi.org/10.4017/gt.2006.04.04.006.00.

[40] J. Nakano, S.I. Tanabe, K.I. Kimura, Differences in perception of indoor environment between Japanese and non-Japanese workers, in: Energy Build., 2002: pp. 615–621. https://doi.org/10.1016/S0378-7788(02)00012-9.

[41] S. Karjalainen, Gender differences in thermal comfort and use of thermostats in everyday thermal environments, Build. Environ. 42 (2007) 1594–1603. https://doi.org/10.1016/j.buildenv.2006.01.009.

[42] S. Karjalainen, Thermal comfort and gender: A literature review, Indoor Air. 22 (2012) 96–109. https://doi.org/10.1111/j.1600-0668.2011.00747.x.

[43] F. Tartarini, P. Cooper, R. Fleming, M. Batterham, Indoor Air Temperature and Agitation of Nursing Home Residents with Dementia, Am. J. Alzheimers. Dis. Other Demen. 32 (2017) 272–281. https://doi.org/10.1177/1533317517704898.

[44] P.O. Fanger, Thermal comfort, Danish Tech. Press. Copenhagen. (1970).

[45] Comité Européen de Normalisation (CEN), CEN Standard EN 15251: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustic, Brussels CEN. (2007).

[46] F.H. Rohles, M.A. Johnson, Thermal comfort in the elderly, ASHRAE Trans. 8 (1972) 131–137.

[47] ASHRAE, ASHRAE Handbook Fundamentals, Am. Soc. Heating, Refrig. Air Cond. Eng. Atlanta. (2009).

[48] N.K. Fukagawa, L.G. Bandini, J.B. Young, Effect of age on body composition and resting metabolic rate, Am. J. Physiol. - Endocrinol. Metab. 259 (1990) E233–E238. https://doi.org/10.1152/ajpendo.1990.259.2.e233.

[49] P.M. Lührmann, B.M. Herbert, C. Krems, M. Neuhäuser-Berthold, A new equation especially developed for predicting resting metabolic rate in the elderly for easy use in practice, Eur. J. Nutr. 41 (2002) 108–113. https://doi.org/10.1007/s003940200016.

[50] J. Goodwin, R.S. Taylor, V.R. Pearce, K.L. Read, Seasonal cold, excursional behaviour,

clothing protection and physical activity in young and old subjects., Int. J. Circumpolar Health. 59 (2000) 195–203.

[51] Y. Jiao, H. Yu, T. Wang, Y. An, Y. Yu, The relationship between thermal environments and clothing insulation for elderly individuals in Shanghai, China, J. Therm. Biol. 70 (2017) 28–36. https://doi.org/10.1016/j.jtherbio.2017.07.002.

[52] H.. Mitchell, Comparative Nutrition of Man and Domestic Animals, 1962. https://doi.org/10.1016/b978-0-12-395551-7.x5001-6.

[53] J. Durnin, Basal Metabolic Rate in Man, Rep. a Jt. FAO/WHO/UNU Expert Consult. Energy Protein Requir. 17 (1981).

[54] M.A. Humphreys, J. Fergus Nicol, The validity of ISO-PMV for predicting comfort votes in every-day thermal environments, in: Energy Build., 2002: pp. 667–684. https://doi.org/10.1016/S0378-7788(02)00018-X.

[55] Z. Wang, B. Cao, B. Lin, Y. Zhu, Investigation of thermal comfort and behavioral adjustments of older people in residential environments in Beijing, Energy Build. 217 (2020) 1–13. https://doi.org/10.1016/j.enbuild.2020.110001.

[56] J. Yang, I. Nam, J.R. Sohn, The influence of seasonal characteristics in elderly thermal comfort in Korea, Energy Build. 128 (2016) 583–591. https://doi.org/10.1016/j.enbuild.2016.07.037.

[57] G. Brager, M. Fountain, C. Benton, E.A. Arens, F. Bauman, A Comparison of Methods for Assessing Thermal Sensation and Acceptability in the Field, in: 1993: pp. 17–39.

[58] G.S. Brager, R.J. De Dear, Thermal adaptation in the built environment: A literature review, Energy Build. 27 (1998) 83–96. https://doi.org/10.1016/s0378-7788(97)00053-4.

[59] M. Humphreys, Outdoor Temperatures and Comfort Indoors., Batim Int Build Res Pr. 6 (1978) 92. https://doi.org/10.1080/09613217808550656.

[60] P. Ole Fanger, J. Toftum, Extension of the PMV model to non-air-conditioned buildings in warm climates, in: Energy Build., 2002: pp. 533–536. https://doi.org/10.1016/S0378-7788(02)00003-8.

[61] N. Baker, M. Standeven, Thermal comfort for free-running buildings, Energy Build. 23 (1996) 175–182. https://doi.org/10.1016/0378-7788(95)00942-6.

[62] R.J. de Dear, G.S. Brager, Developing an adaptive model of thermal comfort and preference, in: ASHRAE Trans., 1998: pp. 145–167.

[63] CIBSE, CIBSE Guide A: Environmental Design, Envrionmental Des. (2015).

[64] R.J. De Dear, G.S. Brager, Thermal comfort in naturally ventilated buildings: Revisions to ASHRAE Standard 55, in: Energy Build., 2002: pp. 549–561. https://doi.org/10.1016/S0378-7788(02)00005-1.

[65] J.F. Nicol, M.A. Humphreys, Adaptive thermal comfort and sustainable thermal standards for buildings, in: Energy Build., 2002: pp. 563–572. https://doi.org/10.1016/S0378-7788(02)00006-3.

[66] F. Haldi, D. Robinson, On the unification of thermal perception and adaptive actions, Build. Environ. 45 (2010) 2440–2457. https://doi.org/10.1016/j.buildenv.2010.05.010.

[67] D. Wang, H. Zhang, E. Arens, C. Huizenga, Observations of upper-extremity skin temperature and corresponding overall-body thermal sensations and comfort, Build. Environ. 42 (2007) 3933–3943. https://doi.org/10.1016/j.buildenv.2006.06.035.

[68] T. Sakoi, K. Tsuzuki, S. Kato, R. Ooka, D. Song, S. Zhu, Thermal comfort, skin temperature distribution, and sensible heat loss distribution in the sitting posture in various asymmetric

radiant fields, Build. Environ. 42 (2007) 3984–3999. https://doi.org/10.1016/j.buildenv.2006.10.050.

[69] Z. Wang, Y. He, J. Hou, L. Jiang, Human skin temperature and thermal responses in asymmetrical cold radiation environments, Build. Environ. 67 (2013) 217–223. https://doi.org/10.1016/j.buildenv.2013.05.020.

[70] W. Liu, Z. Lian, Q. Deng, Use of mean skin temperature in evaluation of individual thermal comfort for a person in a sleeping posture under steady thermal environment, Indoor Built Environ. 24 (2015) 489–499. https://doi.org/10.1177/1420326X14527975.

[71] C. Bae, H. Lee, C. Chun, Predicting indoor thermal sensation for the elderly in welfare centres in Korea using local skin temperatures, Indoor Built Environ. 26 (2017) 1155–1167. https://doi.org/10.1177/1420326X16664563.

[72] B. Tejedor, M. Casals, M. Gangolells, M. Macarulla, N. Forcada, Human comfort modelling for elderly people by infrared thermography: Evaluating the thermoregulation system responses in an indoor environment during winter, Build. Environ. 186 (2020) 107354. https://doi.org/10.1016/j.buildenv.2020.107354.

[73] A.A. Romanovsky, The thermoregulation system and how it works, in: Handb. Clin. Neurol., 2018: pp. 3–43. https://doi.org/10.1016/B978-0-444-63912-7.00001-1.

[74] T.E. Wilson, R. Zhang, B.D. Levine, C.G. Crandall, Dynamic autoregulation of cutaneous circulation: Differential control in glabrous versus nonglabrous skin, Am. J. Physiol. - Hear. Circ. Physiol. 289 (2005) H385–H391. https://doi.org/10.1152/ajpheart.00622.2004.

[75] L. Walløe, Arterio-venous anastomoses in the human skin and their role in temperature control, Temperature. 3 (2016) 92–103. https://doi.org/10.1080/23328940.2015.1088502.

[76] S. Van Craenendonck, L. Lauriks, C. Vuye, J. Kampen, A review of human thermal comfort experiments in controlled and semi-controlled environments, Renew. Sustain. Energy Rev. 82 (2018) 3365–3378. https://doi.org/10.1016/j.rser.2017.10.053.

[77] H.M. Hodkinson, Evaluation of a mental test score for assessment of mental impairment in the elderly, Age Ageing. 1 (1972) 233–238. https://doi.org/10.1093/ageing/1.4.233.

[78] K. Rockwood, X. Song, C. MacKnight, H. Bergman, D.B. Hogan, I. McDowell, A. Mitnitski, A global clinical measure of fitness and frailty in elderly people, CMAJ. 173 (2005) 489–495. https://doi.org/10.1503/cmaj.050051.

[79] K. Parsons, The thermal properties of clothing, in: Hum. Therm. Environ., 2021: pp. 178–216. https://doi.org/10.1201/9780203302620-16.

[80] D.A. McIntyre, Thermal sensation. A comparison of rating scales and cross modality matching, Int. J. Biometeorol. 20 (1976) 295–303. https://doi.org/10.1007/BF01553586.

[81] F. Jazizadeh, F.M. Marin, B. Becerik-Gerber, A thermal preference scale for personalized comfort profile identification via participatory sensing, Build. Environ. 68 (2013) 140–149. https://doi.org/10.1016/j.buildenv.2013.06.011.

[82] S. Gerrior, W.Y. Juan, P. Basiotis, An easy approach to calculating estimated energy requirements, Prev. Chronic Dis. 3 (2006) A129.

[83] M.D. Mifflin, S.T. St Jeor, L.A. Hill, B.J. Scott, S.A. Daugherty, Y.O. Koh, A new predictive equation for resting energy expenditure in healthy individuals, Am. J. Clin. Nutr. 51 (1990) 241–247. https://doi.org/10.1093/ajcn/51.2.241.

[84] Z. Wu, N. Li, H. Cui, J. Peng, H. Chen, P. Liu, Using upper extremity skin temperatures to assess thermal comfort in office buildings in Changsha, China, Int. J. Environ. Res. Public Health. 14 (2017) 1092. https://doi.org/10.3390/ijerph14101092.

[85] F. Haldi, D. Robinson, Modelling occupants' personal characteristics for thermal comfort prediction, Int. J. Biometeorol. 55 (2011) 681–694. https://doi.org/10.1007/s00484-010-0383-4.

[86] M.H. Hasan, F. Alsaleem, M. Rafaie, Sensitivity study for the PMV thermal comfort model and the use of wearable devices biometric data for metabolic rate estimation, Build. Environ. 110 (2016) 173–183. https://doi.org/10.1016/j.buildenv.2016.10.007.

[87] D.P. Reidlinger, J.M. Willis, K. Whelan, Resting metabolic rate and anthropometry in older people: A comparison of measured and calculated values, J. Hum. Nutr. Diet. 28 (2015) 72–84. https://doi.org/10.1111/jhn.12215.

[88] World Health Organization, WHO Housing and health guidelines, 2018. https://www.who.int/publications/i/item/9789241550376.

[89] P.C. Austin, E.W. Steyerberg, Events per variable (EPV) and the relative performance of different strategies for estimating the out-of-sample validity of logistic regression models, Stat. Methods Med. Res. 26 (2017) 796–808. https://doi.org/10.1177/0962280214558972.

[90] D.S. Courvoisier, C. Combescure, T. Agoritsas, A. Gayet-Ageron, T. V. Perneger, Performance of logistic regression modeling: Beyond the number of events per variable, the role of data structure, J. Clin. Epidemiol. 64 (2011) 993–1000. https://doi.org/10.1016/j.jclinepi.2010.11.012.

[91] M. van Smeden, K.G.M. Moons, J.A.H. de Groot, G.S. Collins, D.G. Altman, M.J.C. Eijkemans, J.B. Reitsma, Sample size for binary logistic prediction models: Beyond events per variable criteria, Stat. Methods Med. Res. 28 (2019) 2455–2474. https://doi.org/10.1177/0962280218784726.

[92] K.G.M. Moons, J.A.H. de Groot, W. Bouwmeester, Y. Vergouwe, S. Mallett, D.G. Altman, J.B. Reitsma, G.S. Collins, Critical Appraisal and Data Extraction for Systematic Reviews of Prediction Modelling Studies: The CHARMS Checklist, PLoS Med. 11 (2014). https://doi.org/10.1371/journal.pmed.1001744.

[93] M. Pavlou, G. Ambler, S. Seaman, M. De iorio, R.Z. Omar, Review and evaluation of penalised regression methods for risk prediction in low-dimensional data with few events, Stat. Med. 35 (2016) 1159–1177. https://doi.org/10.1002/sim.6782.

[94] E.W. Steyerberg, M.J.C. Eijkemans, F.E. Harrell, J.D.F. Habbema, Prognostic modelling with logistic regression analysis: A comparison of selection and estimation methods in small data sets, Stat. Med. 19 (2000) 1059–1079. https://doi.org/10.1002/(SICI)1097-0258(20000430)19:8<1059::AID-SIM412>3.0.CO;2-0.

[95] Y. Xie, J. Liu, T. Huang, J. Li, J. Niu, C.M. Mak, T. cheung Lee, Outdoor thermal sensation and logistic regression analysis of comfort range of meteorological parameters in Hong Kong, Build. Environ. 155 (2019) 175–186. https://doi.org/10.1016/j.buildenv.2019.03.035.

[96] C. Tweed, N. Humes, G. Zapata-Lancaster, The changing landscape of thermal experience and warmth in older people's dwellings, Energy Policy. 84 (2015) 223–232. https://doi.org/10.1016/j.enpol.2015.03.011.

[97] A. Hansen, P. Bi, D. Pisaniello, M. Nitschke, G. Tucker, J. Newbury, A. Kitson, E. Dal Grande, J. Avery, Y. Zhang, L. Kelsall, Heat-health behaviours of older people in two Australian states, Australas. J. Ageing. 34 (2015) E19–E25. https://doi.org/10.1111/ajag.12134.

[98] E. Oikonomou, R. Raslan, R. Gupta, A. Howard, A. Mavrogianni, Care Home Overheating Audit Pilot Project - Executive Summary, Mayor London, GLA, London, UK. (2020).