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A comparison of air temperature thresholds for warm thermal discomfort between pre- and post-menopausal women

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ABSTRACT

Our aim was to compare the ambient temperature thresholds for warm thermal discomfort, thermal unacceptability, and preference for cooler environment between post- and pre-menopausal women at different metabolic rates. A total of 38 women (15 pre-menopausal (46 ± 5 years); 23 post-menopausal (55 ± 3 years)), completed up to 3 experimental trials at different metabolic rates (1.2 MET, 1.8 MET, 2.5 MET) generated by intermittent stepping throughout an air temperature ramp protocol. Ambient air temperature thresholds for warm thermal discomfort (thermal sensation rating of +1.5), warm thermal unacceptability, and a preference for a cooler environment, were determined. Skin temperature at 12 points was measured throughout. While a higher metabolic rate yielded a lower air temperature threshold for warm thermal discomfort ($P < 0.001$), there was no difference ($P = 0.61$) between pre-menopausal (28.7 ± 2.3 °C) and post-menopausal (28.5 ± 2.4 °C) women, irrespective of metabolic rate. The threshold of thermal unacceptability and the temperature at which a preference to be cooler was expressed were decreased by 1 °C, regardless of metabolic rate in post-menopausal women ($P = 0.021$; $P = 0.049$). Mean body T_{sk} at the thresholds for warm thermal discomfort, thermal unacceptability, and preference for cooler temperature (all $P > 0.05$) did not differ between pre-menopausal and post-menopausal women. However, the forehead T_{sk} thresholds for thermal unacceptability (pre-menopausal: 34.5 ± 1.1 °C; post-menopausal: 33.9 ± 1.2 °C; $P = 0.005$) and preference for cooler temperature (pre-menopausal: 34.2 ± 1.2 °C; post-menopausal: 33.7 ± 1.3 °C; $P = 0.025$) were lower in post-menopausal women. These data indicate that while the temperature threshold for warm thermal discomfort is unaltered by menopause status, post-menopausal women report an environment to be unacceptably warm, and express a preference for a cooler temperature, at a lower ambient and forehead skin temperature.

1. Introduction

In recent years, the global workforce has substantially increased in age and female worker participation rates. From 1990 to 2017, the increase in female workforce participation of women aged 55–65 years across 23 countries ranged from as little as 13%–363%, with a mean increase of 107%, and 9 countries exceeding 100% increases [1,2]. The significance of this phenomenon is punctuated by the menopause transition, a natural period of change marking the end of the reproductive years.

Within this period of change, peri-menopause describes the onset of symptoms, while the menopause itself represents the final menstrual period, and post-menopause the years beyond the menopause. Many symptoms manifest during the menopause transition, the most renowned of which is known as the “hot flush or flash”, which describes transient periods of perceived internal heat, reddening of the skin, and sweating. Lasting an average of 3–5 min [3–6], the hot flush can be acutely distressing, causing disruption and embarrassment for peri- and post-menopausal women [7,8].

Previous literature pertaining to the thermal comfort of women within indoor environments has consistently demonstrated a preference for warmer air temperatures, and a greater thermal discomfort where the ambient conditions deviate from a preferred neutral state when compared with males in both warm and cool conditions [9–11].

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Moreover, females have been shown to be more thermally sensitive to heat across all regions of the body when compared to males [11,12]. Nevertheless, there remains very little evidence that female thermal sensation or comfort deviates when compared with other females during menstruation, pregnancy, or the menopause transition [11,13]. Yet, anecdotally, postmenopausal women have described chronic thermal comfort changes relative to their previous experiences, particularly where hot flushes are present.

A recent exploratory analysis of indoor workers found that women of peri-menopausal age (40–50 years) reported an increased perception of warmth while expressing thermal dissatisfaction more frequently, preference for lower air temperatures along with increased airflow when compared to females in other age categories, and males in all age categories [14]. While the age groups could not be defined as per the menopausal age guidelines for natural menopause (40–55 years) and menopausal status was not reported, the data provide a compelling argument to investigate the potential thermal comfort changes that occur throughout the menopause transition.

The aim of this study was to compare the upper ambient temperature thresholds for warm thermal discomfort, and changes in thermal acceptability and preference in post-versus pre-menopausal women at different metabolic rates that are representative of common work activities. We hypothesised that relative to a pre-menopausal group of women, post-menopausal women would demonstrate a lower air temperature threshold for warm thermal discomfort, along with reduced threshold temperatures for thermal unacceptability and preference for cooler temperatures.

2. Methods

2.1. Participants

The study was approved by the University of Sydney Human Research Ethics Committee (2019/174). A total of 38 participants (23 post-menopausal and 15 pre-menopausal women) consented to participate and completed between 1 and 3 experimental trials. Participants were asked to refrain from consuming alcohol, caffeine, and engaging in exercise during the 24 h prior to their experimental trials. Participants between 40 and 60 years were recruited to capture the natural age of menopause, but also minimise any thermoregulatory differences that may have arisen due to age, rather than menopause status. The menopause status of participants was self-reported by participants relative to their symptoms and menstrual activity as defined by STRAW +10 [15]. For the purpose of comparisons between symptomatic and non-symptomatic women, pre-menopausal (within reproductive years, no symptoms of menopause) and post-menopausal (post-reproductive years, experiencing symptoms of the menopause) women were recruited to clearly delineate the menopause transition from the reproductive years within a similar age range. Further, participants were not prescribed any medications that could impair or influence normal thermoregulatory function before their experimental trials (e.g. antiadrenergics, anticholinergics, antidepressants, antihistamines, antihypertensives, antipsychotics, diuretics, sympathomimetics) and were not suffering from any cardiovascular or metabolic diseases/conditions.

Participant characteristics are detailed in Table 2.

2.2. Instrumentation

Skin temperature was measured at 12 skin sites (forehead, chest, upper back, lower back, stomach, forearm, hand, thigh, hamstring, shin, calf, foot) on the left side of the body using wireless iButtons (DS1922-F5#, Embedded Data Systems, Lawrenceburg, KY, USA), secured to the skin with hypoallergenic surgical tape (3 M Transpore 1527–1). Mean skin temperature was estimated using a 12-point weighted mean according to Hardy & DuBois [16].

Table 2
Participant characteristics by experimental trial.

Experimental Trial Group	Age, years			Weight, kg
	Range	Mean ± SD	Range	Mean ± SD
Seated Work				
Pre-menopausal (n=15)	40–53	46 ± 4	43.0–100.1	63.5 ± 17.5
Post-menopausal (n=15)	52–60	57 ± 2	41.0–100.8	72.3 ± 15.8
Standing Work				
Pre-menopausal (n=15)	40–53	46 ± 4	43.0–100.1	63.5 ± 17.5
Post-menopausal (n=15)	51–60	56 ± 3	41.0–94.3	71.9 ± 14.6
Moving Work				
Pre-menopausal (n=15)	40–53	46 ± 4	43.0–100.1	63.5 ± 17.5
Post-menopausal (n=15)	51–60	55 ± 3	41.0–94.10	68.3 ± 14.5

2.3. Perceptual indices

Thermally comfortable assessments were assumed to correspond with the central three votes on the ASHRAE 7-point thermal sensation scale (−3 *cold*, −2 *cool*, −1 *slightly cool*, 0 *neutral*, +1 *slightly warm*, +2 *warm*, +3 *hot*), as described in Fanger's *Predicted Percentage Dissatisfied* thermal index [9]. Participants were able to mark anywhere along a solid line on an 18 cm scale. Further questions relating to thermal acceptability and preference followed the thermal sensation vote, as described by Deuble and de Dear [17]:

- Is the current air temperature acceptable? Yes/No
- Would you prefer to be cooler/no change/warmer?

Where hot flushes were reported to occur by the participant during an experimental trial, the nearest perceptual measures taken before and after a hot flush were used, to ensure none of the thermal comfort, acceptability, or preference thresholds were altered by the presence of a hot flush. If the hot flush was perceived to be of a greater magnitude after the flush had ceased, that is the thermal comfort level changed, the highest subjective assessments were reported.

2.4. Experimental protocol

Participants attended the Thermal Ergonomics Laboratory at the University of Sydney, Australia, for a minimum of one visit to complete a preliminary session directly followed by an experimental trial (same day). The preliminary trial included the informed consent process, equipment familiarity, and protocol familiarity. Where participants elected to complete more than one trial, a minimum of 48 h separated the trials. The experimental trials began with a urine sample (Atago, Japan) to ensure adequate hydration for females (<1.020) [18]. If participants were not euhydrated upon arrival, they were given 200–300 ml of water to drink *ad libitum* before entering the chamber [19]. Participants were then required to change into standardised work attire provided for the study (high visibility shirt and cotton drill shorts) with their own running shoes and socks (total insulation: ~0.3 Clo). The standardised work attire consisted of a loose fit collared shirt (100% Microfibre (polyester/nylon blend): AS/NZ 4602.1 class D high visibility) and knee-length drill shorts (100% cotton). The clothing insulation (Clo) of the standardised participant attire was attained during pilot work on a thermal manikin (PT Teknik, Espergærde, Denmark).

Upon initial entry into the climate chamber (25 °C, 35%RH), instrumentation was performed (as per section 2.2) whilst participants sat quietly. An intermittent step protocol was employed to attain the simulated work activity in a 1:1 ratio (2.5 min or work and rest) performed on a 15-cm exercise step (Everfit, VIC, Australia). The step rate for each metabolic rate was determined and validated through respiratory gas analysis in pilot trials. Upon the commencement of the allotted step rate, the temperature in the climate-controlled chamber was dropped to the respective starting temperature based on the adjusted PMV for the required metabolic work (1.8 MET: 24 °C, 2.5 MET: 20 °C), while the air temperature in the 1.2 MET trial was maintained at 25 °C. The period of time in which the air temperature was dropped to accommodate the required work was maintained at 20 min for all trials, irrespective of work rate. Air temperature was then ramped, whilst perceptual data were collected every 10 min throughout the trial. A schematic of the experimental trial timeline is depicted below in Fig. 2.

2.5. Experimental design

To answer the research question which pertains to workplace contexts, we utilised a climate chamber and replicated the workplace activity and clothing of indoor warehouse workers. Participants performed up to 3 experimental trials, each differing in metabolic rate (1.2 MET, 1.8 MET, 2.5 MET). Participants were offered the option to participate in 1, 2, or 3 experimental trials, resulting in a total of 90 experimental trials completed. The physical work requirements (1.2 MET, 1.8 MET, 2.5 MET) were based on preliminary data acquired from warehousing environments from menopausal women performing typical work tasks with a breath-by-breath gas analyser (Quark CPET, Cosmed, NSW, Australia). The environmental conditions for the beginning of the three experimental trials were calculated with the Predicted Mean Vote (PMV) model [9], which incorporates clothing insulation (Clo), air flow (m/s), relative humidity (%), and a metabolic equivalent (MET) to provide a predicted operative temperature expected to elicit an average vote of "neutral" on the ASHRAE thermal sensation scale (i.e., PMV = 0). The predicted neutral temperatures (°C) with a Clo of 0.3, fixed air flow (~0.12 m/s), and relative humidity (~35%) were calculated for each metabolic rate and rounded to the nearest integer (i.e., 25 °C, 24 °C, and 20 °C) to elicit a Predicted Percentage Dissatisfaction (PPD) of less than 10% for the beginning of each experimental trial [9]. The air temperature ramp then increased from this starting temperature, which correlated with less than 10% PPD, to the end of the trial temperature (by > 8 °C) where PPD was calculated to be greater than 70%.

To determine the upper air temperature threshold for warm thermal discomfort, a fixed relative humidity, air temperature ramp protocol was utilised whereby air temperature increased by 1 °C every 20 min. The target air temperature was reached for each incremental step within the first ~2 min of each period and then stabilised for the remainder of the 20 min period. Step duration was chosen to enable the participant adequate time to perceptually adjust to a change in conditions according to ANSI/ASHRAE 55 [20], where specific thresholds for air temperature increases and the duration of change are specified for air temperature ramps and drifts to maintain thermal comfort. A thermal sensation vote of +1.5, i.e. midway between "*slightly warm*" and "*warm*" [21] was used to identify the threshold for warm thermal discomfort, while thermal unacceptability and thermal preference for cooler conditions were indicated with binary questions (accpetable and unacceptable or warmer, no change, and cooler, respectively), see Fig. 1 for a visual depiction.

2.6. Statistical analysis

A two-way ANOVA was employed to determine the main effects of physical work intensity (3 levels: seated (1.2 METs), standing (1.8 METs), and moving (2.5 METs) work) and menopause status (2 levels: pre-menopausal and post-menopausal) on the air temperature at which a) warm thermal discomfort was identified (+1.5 from neutral thermal sensation vote), b) thermal unacceptability was reached, and c) thermal preference for a cooler environment was reported. As the face has been previously defined as a highly thermally sensitive area [22–24], local skin temperature of the forehead, as well as mean skin temperature at the point of thermal discomfort (+1.5 from neutral thermal sensation vote), thermal unacceptability, and thermal preference were individually analysed as dependent variables with the same two-way ANOVA model described above. All data are mean ± SD unless otherwise stated.

3. Results

3.1. Air temperature thresholds

The data in Fig. 3A–C depicts the air temperature thresholds at which warm thermal discomfort (panel A), thermal unacceptability (panel B), and a change in thermal preference for a cooler environment (panel C) was reached for post-menopausal women relative to pre-menopausal

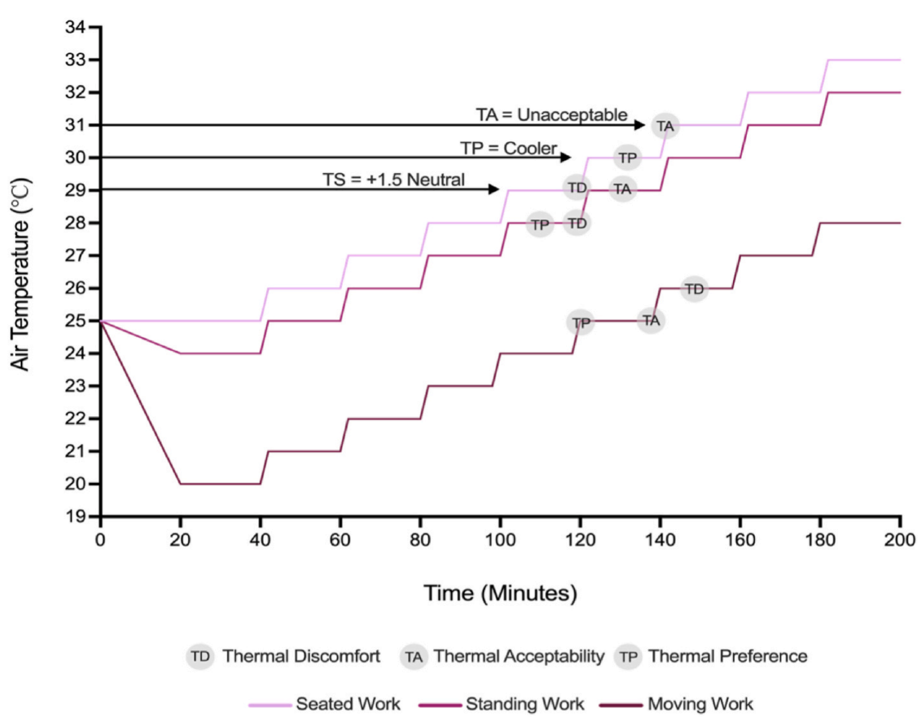

Fig. 1. Visual representation of the air temperature ramp protocol for each workload with the temperature thresholds for discomfort, acceptability, and preference (data points depicted are for illustration purposes only).

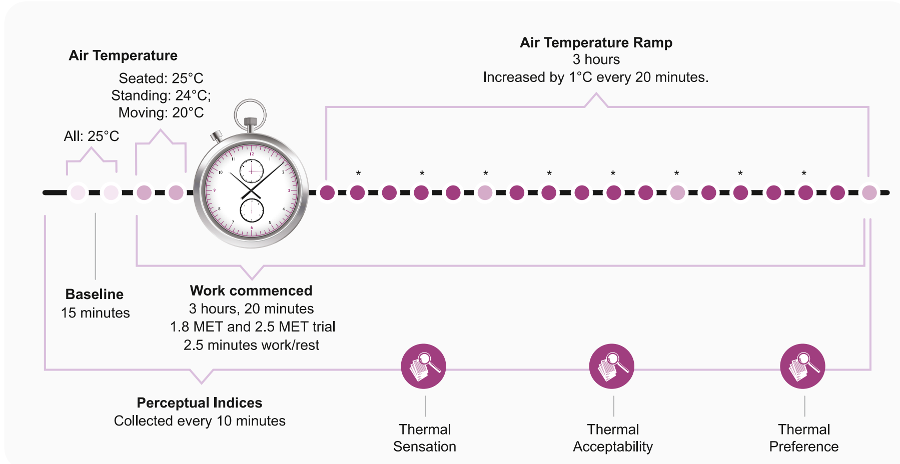

Fig. 2. Visual representation of the trial timeline, from baseline to trial completion.

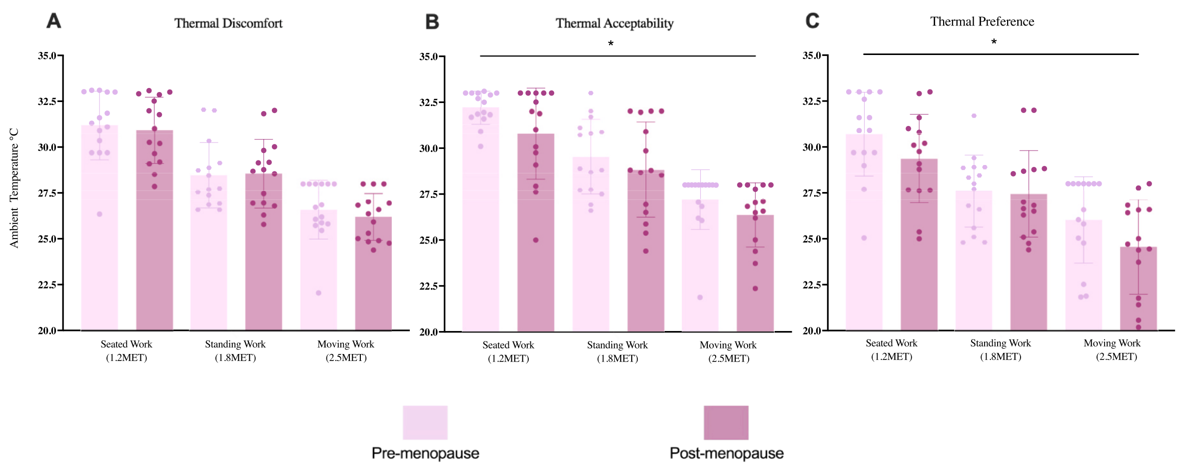

Fig. 3. The air temperature threshold for warm thermal discomfort (panel A), thermal acceptability (panel B), and thermal preference for cooler conditions (panel C) for pre- and post-menopausal women at three different metabolic rates. ** Indicates a main effect of menopause status (<0.05).*

women at each of the three work intensities. Work at higher metabolic rates significantly reduced the air temperature threshold at which all women experienced warm thermal discomfort, thermal unacceptability, and the preference for cooler conditions ($P < 0.001$). Irrespective of metabolic rate, the threshold air temperatures for warm thermal discomfort (+1.5 from neutral) were not different between pre- and post-menopausal groups ($P = 0.61$; interaction $P=0.85$). Nevertheless, post-menopausal women reported thermal unacceptability ($P = 0.021$; interaction $P = 0.76$) and a preference for cooler conditions ($P = 0.049$; interaction $P = 0.49$) at a lower air temperature than the pre-menopausal women across all three metabolic rates. Specifically, post-menopausal women reported thermal unacceptability and a preference for cooler conditions ~1 °C lower than pre-menopausal women in the same conditions.

3.2. Mean skin temperature thresholds

Similarly, work at a higher metabolic rate significantly reduced the mean skin temperature threshold at which all women, irrespective of menopausal status, experienced warm thermal discomfort, thermal unacceptability, and the preference for cooler conditions ($P < 0.001$). However, no differences were observed for the mean skin temperature thresholds at which thermal discomfort, thermal unacceptability, or thermal preference (Discomfort: $P = 0.98$; interaction $P = 0.82$; Acceptability: $P = 0.11$; interaction $P = 0.99$; Preference: $P = 0.22$; interaction $P = 0.87$) were reported (Fig. 4A–C).

3.3. Forehead skin temperature thresholds

A greater metabolic rate significantly reduced the forehead skin temperature thresholds for warm thermal discomfort, thermal acceptability, and thermal preference irrespective of menopausal status ($P < 0.001$) (Fig. 5A–C). The local forehead skin temperature thresholds for warm thermal discomfort were not different between pre- and post-menopausal groups ($P = 0.13$; interaction $P = 0.88$), yet the forehead temperature threshold for thermal unacceptability ($P = 0.005$; interaction $P = 0.88$) and thermal preference ($P = 0.026$; interaction $P = 0.78$) were significantly lower in the post-menopausal group. Specifically, post-menopausal women experienced ~0.5 °C lower forehead skin temperature threshold for discomfort than pre-menopausal women in the same conditions.

4. Discussion

The present study compared the temperature thresholds for warm thermal discomfort, thermal unacceptability, and changes in thermal preference of pre-menopausal and post-menopausal women performing physical activity at three different metabolic rates that are representative of common occupational tasks in an indoor work environment. While the air temperature threshold for warm thermal discomfort was

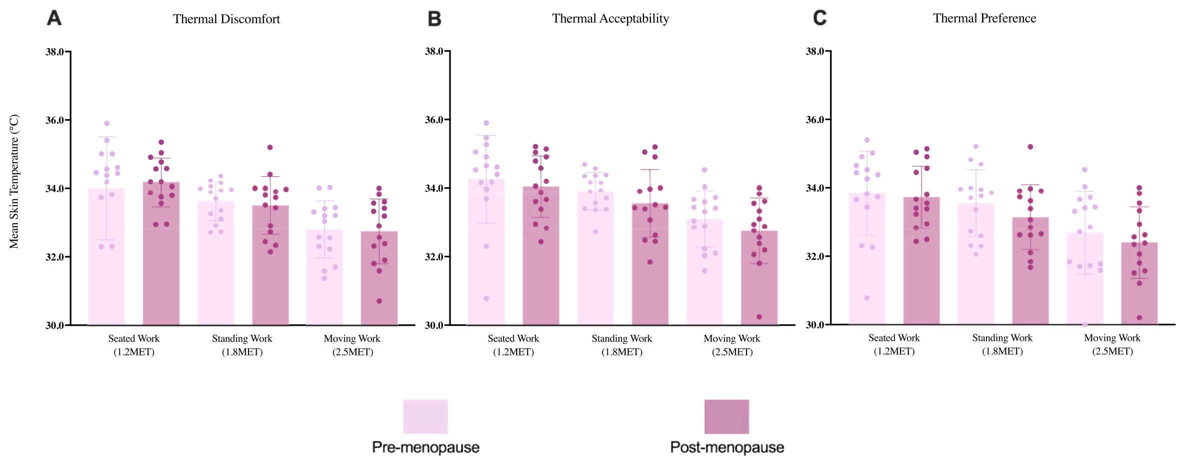

Fig. 4. The mean skin temperature threshold for warm thermal discomfort (panel A), thermal acceptability (panel B), and thermal preference for cooler conditions (panel C) for pre- and post-menopausal women at three different metabolic rates. ** Indicates a main effect of menopause status (<0.05).*

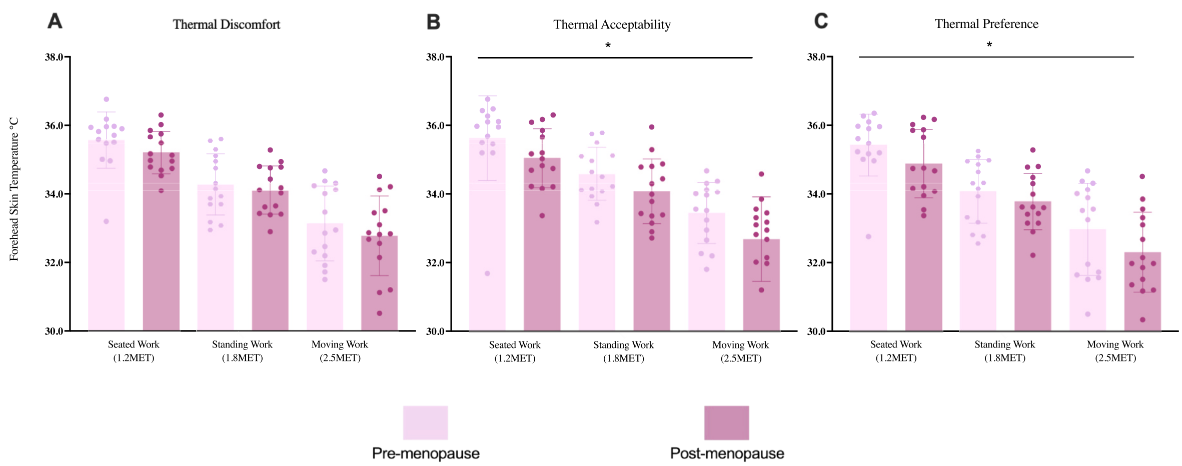

Fig. 5. The forehead skin temperature threshold for warm thermal discomfort (panel A), thermal acceptability (panel B), and thermal preference for cooler conditions (panel C) for pre- and post-menopausal women at three different metabolic rates. ** Indicates a main effect of menopause status (<0.05).*

not different between pre- and post-menopausal women, the air temperature threshold for thermal unacceptability and a preference for cooler conditions was significantly lower (by ~1 °C) in post-menopausal women. These findings highlight the chronic impacts of menopause status on thermal comfort, independent of the more commonly considered, but transient, menopausal hot flush, which may influence the thermal satisfaction of peri- or post-menopausal women within indoor environments.

4.1. Thermal sensation votes with air temperature and hot flushes

While females have consistently demonstrated a preference for warmer air temperatures and are generally more dissatisfied with deviations from preferred temperatures [9–11], these findings have all been reported relative to males. To date, apart from Xiong et al. [14], no literature, to the best of our knowledge, has reported differences between females of different age groups, even throughout the menstrual or ovarian cycle, where slight deviations in core body temperature and thermoeffector responses to heat and cold stimuli can occur [13,23]. Although quantitative and qualitative survey analysis has reported menopausal women wanting more control over their immediate thermal environment with respect to both air temperature and air flow [25–27], the potential effect of menopause status on thermal comfort has not specifically been investigated.

Recent research [14] which aimed to identify age-related changes in thermal comfort between women of different age brackets was conducted retrospectively with women of peri-menopausal age (40–49 years) reported to feel warmer, prefer air cooler temperatures, and find the environment less acceptable than all-male co-workers and younger or older female co-workers [14]. The age bracket which includes women aged 50–60 years is arguably just as important due to the average natural age of the menopause being between 47 and 52 years for most women across the globe [28]. Thus, the impact of thermal comfort changes within that study was limited to the peri-menopausal aged women, rather than post-menopausal women who are well known to experience the extensive symptoms of menopause, even beyond the age of 60 years [29–31].

In contrast, the findings of the present study demonstrate that post-menopausal women report lower air temperature thresholds for both thermal acceptability and when they prefer to be in cooler conditions by ~1–2 °C. While no differences were reported in the thermal sensation votes, which impacted the inferred thermal discomfort threshold, the relevance of the thermal unacceptability and preference votes describe a level of dissatisfaction or thermal discomfort in the environment alone. The most discernible difference between the current study and previous work is the comparison between women of a similar age who have not experienced the hormonal decline associated with the menopause, while also controlling for the presence of hot flushes. While the thermal comfort changes may be related to the presence of hot flushes, the data herein demonstrate that there are more chronic changes in perception within post-menopausal women which appears to be unrelated to the acute occurrence of hot flushes.

4.2. Thermal sensation and comfort in relation to skin temperature

The importance of skin temperature, as an interface with the direct thermal environment, represents perception (sensory integration). While mean skin temperature across the body is representative of segmental body surface area as a contribution to a whole, there is potential that more thermally sensitive areas of the body may take precedence in driving changes in thermal comfort within a given environment. The mean skin temperature at which thermal discomfort occurred was not different between pre- and post-menopausal women, however, the forehead skin temperature at which thermal acceptability and thermal preference were reported were lower in post-menopausal women. The influence of facial or forehead skin temperature in this regard may be due to the increased thermal sensitivity experienced within these regions [21,22,32], representing the most likely contributor to what is felt and perceived from a physiological perspective. Recently when compared by sex, young females demonstrated increased heat perception of the face alongside increased thermal discomfort responses when contrasted with males [12].

However, the sensitivity of the face alone does not describe the differences between the thermal acceptability and preference responses of the pre-menopausal and post-menopausal women. Research has demonstrated that the degree of change in local skin temperature or the perception of change in skin temperature can drive thermal behaviour which occurs independent of any core temperature changes [33–37]. Yet, this also does not explain why mean skin temperature thresholds for thermal sensation, unacceptability, and preference were not different between pre- and post-menopausal women. Importantly, the data from this study, which collected 12-sites of skin temperature data across the body, showed no increases in skin temperature therefore a difference or change in skin temperature was likely not the cause of any perceptual changes to thermal sensation, unacceptability, or preference.

It could be that the history of symptoms such as the hot flush alters what is thermally unacceptable and preferable, such that the likelihood of experiencing a more intense and uncomfortable hot flush may be perceived to be associated with increased air temperatures [7]. In this way, there may be negative memories associated with the occurrence of a hot flush with increased facial skin temperatures, as skin temperature determines our sensation and perception of the environment, and thermally sensitive areas provide the quickest information. Within this study ~65% of the post-menopausal women had a hot flush during at least one trial, while the rest did not experience a hot flush during a trial, therefore the acute sensation or residual effects of a hot flush were not the cause of the perceptual changes.

The concept of negative memories has been previously described by de Dear [38] where an environmental stimulus creates negative associations, therefore influencing the future perceptions and interpretations of that environment from a thermal comfort perspective. The importance of facial skin temperatures has been demonstrated by a preference for facial cooling in response to warm thermal stimuli as a means to feel cooler and improve whole-body thermal comfort [22,39]. Together, the results and literature indicate facial skin temperature to be of relevance to the thermal acceptability and preference of post-menopausal women and may provide future avenues for relief of thermal discomfort within this population.

4.2.1. Limitations and delimitations

By necessity and due to the mean natural age of the menopause in Australia (51 years) age discrepancies are reported between the pre- and post-menopausal participants group within each workload (Table 2) which may have contributed to the outcomes. While previous research in Japanese cohorts have demonstrated some significant decreases in thermal sensitivity and sensation in older cohorts [40,41], those studies included only male participants and adults older than 65 years. Specifically, Takeda et al. [40] only reported local changes in thermal perception at the forearm of older participants, while Tochihara et al. [41] reported non-uniform regional decreases in warmth sensitivity in older males (64-68y). Within a European context, again with an all-male cohort, Coull et al. [42] reported no differences in thermal comfort and sensation votes between young adult males (20–30 years) and older adult males (60–80 years), yet thermal sensitivity to cold and warm stimuli was decreased in the older males. In contrast, a thermal comfort study within indoor settings surveying 384 men and women aged 60–97 years reported no significant differences in thermal sensation or comfort between sexes [43].

Moreover, the expected physiological changes which occur with age that could alter thermal perception (thermoeffector responses: sweating, vasodilation) only tend to emerge beyond ~60 years [44–46]. Specifically, reported declines in sweating capacity associated with age predominantly occur over the age of 55 [46], yet a comparison of post-menopausal women (58 ± 2 y) with slightly younger women (38 ± 2 y) found no differences in sweat output that would alter thermoregulation between the two groups [47]. Further, skin blood flow responses to whole-body heat stress have only demonstrated significant differences in younger cohorts above the age of 60 years [44,45]. It therefore seems unlikely that any deviation in the subjective thermal responses between the two groups in the present study can be ascribed to a primary ageing effect. Rather, the differences in thermal acceptability and preference votes can be confidently attributed to differences in reproductive status.

Lastly, due to the time commitment of laboratory studies, some participants were not able to complete all 3 experimental trials, which increased the pool of participants required to complete this study by six. However, personal characteristics that had potential to influence the results of this study were strictly controlled. Beginning with health status, all participants were screened for metabolic, respiratory, and cardiovascular disease which could infer differences in thermoregulation or perception prior to participation. Second, differences in fitness were relatively low given the requirement of physical exercise (~100 min) throughout the exercise trials, moreover, research had demonstrated that fitness (defined as maximal aerobic capacity; VO_{2max}) has minimal influence on thermoregulation [48,49], therefore any centrally moderated responses to heat (core temperature, sweating, vasodilation) would not have been significantly different amongst the research participants. Finally, body fatness and fitness has previously described minimal variation in thermoeffector action (sweating) or core temperature responses, particularly fitness as described by VO2max [48,49]. These findings are further supported by thermal perception research which determined that body fatness did not influence thermal perception [9,50].

4.3. Implications

It is evident that thermal unacceptability and preference are impacted by menopause status, such that post-menopausal women have a lower air temperature threshold for each. While hot flushes may have acute thermal comfort impacts, this study attests to more chronic changes in thermal unacceptability and preference in postmenopausal women which is not directly or acutely caused by a hot flush. The perception that during a hot flush would be the only time that peri- or post-menopausal women may experience discomfort is refuted by the present data. Changes in thermal comfort demonstrated within this study may be a chronic result of the hot flush, yet hot flushes were not experienced by all of the post-menopausal women within this study during the experimental trials. For example, of the 23 post-menopausal women who participated within this study, 15 women reported a hot flush during at least 1 experimental trial. Therefore, the changes in thermal perception cannot be attributed to the presence of hot flushes alone.

Within workplace settings, it is important to consider that unpleasant warm sensation can negatively impact cognition and complex tasks [51,52], which in turn, could result in reduced workplace performance in peri- or post-menopausal women. The impact of hot flushes has been reported within large population studies, with menopausal women reporting reduced quality of life [53], mental wellbeing [54], and social interactions [55]. Moreover, menopausal women have reported decreased ability to perform workplace tasks [56,57], with approximately half considering leaving the workforce due to their menopausal symptoms [58]. With 71% of menopausal women reporting dissatisfaction with workplace air temperatures, poor ventilation, or perceived heat within their work environment [26], it is clear that menopausal women need effective and evidence-based strategies to find relief from their hot flushes and chronic discomfort.

While the present findings are restricted to a relatively small sample of pre- and post-menopausal women, the main outcomes indicate that post-menopausal women prefer an ambient temperature that is ~1–2 °C cooler than pre-menopausal women. Notwithstanding the implementation of lower thermostat set-point temperatures on air coolers (i.e., air conditioning), which are often not financial and practically viable in large workspaces, potential strategic modifications to the built environment to achieve a lower ambient workplace temperature are limited. “Spot cooling” can help create thermal gradients across workspaces that provide access to cooler areas for post-menopausal women working in environments that enable free mobility between workstations [59]. While such a solution may not be well suited to most work environments, reductions in air temperature can be substituted with elevations in air movement to enable similar rates of sensible heat loss without additional air cooling [60]. At the building level, additional indoor air flow can be achieved by increasing cross-ventilation through open windows, but with a potential cost of higher air temperatures if outdoor conditions are warmer than indoors. At the personal level, self-regulated air flow with small personal fans can effectively enable workers to achieve thermal comfort while being portable and compatible with a variety of settings, e.g., attached to surrounding structures, embedded within chairs [61]. Given the potential importance of facial skin temperature thresholds identified within the present study, convective cooling could be best strategically targeted at the face to achieve optimal perceptual cooling [62].

5. Conclusion

The present study demonstrates the impact of menopause status on women’s thermal comfort within indoor settings. Whilst the air temperature threshold for thermal comfort was unaltered by menopause status, lower air temperature thresholds were reported for both thermal acceptability (pre-menopausal: 29.6 ± 2.5 °C; post-menopausal: 28.7 ± 2.2 °C; P = 0.021) and thermal preference (pre-menopausal: 28.1 ± 2.4 °C; post-menopausal: 27.2 ± 2.4 °C; P = 0.049) when compared to pre-menopausal women. Moreover, the forehead skin temperature threshold for thermal comfort was unaltered by menopause status, yet lower forehead skin temperature thresholds were reported for both thermal acceptability (pre-menopausal: 34.5 ± 1.1 °C; post-menopausal: 33.9 ± 1.2 °C; P = 0.005) and thermal preference (pre-menopausal: 34.2 ± 1.2 °C; postmenopausal: 33.7 ± 1.3 °C; P = 0.025) when compared with pre-menopausal women.

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CRediT authorship contribution statement

Sarah Carter: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nicole T. Vargas:** Writing – review & editing, Supervision, Formal analysis. **Richard de Dear:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Kirsten I. Black:** Writing – review & editing, Supervision, Project administration. **Ollie Jay:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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