Local wearable cooling may improve thermal comfort, emotion, and cognition

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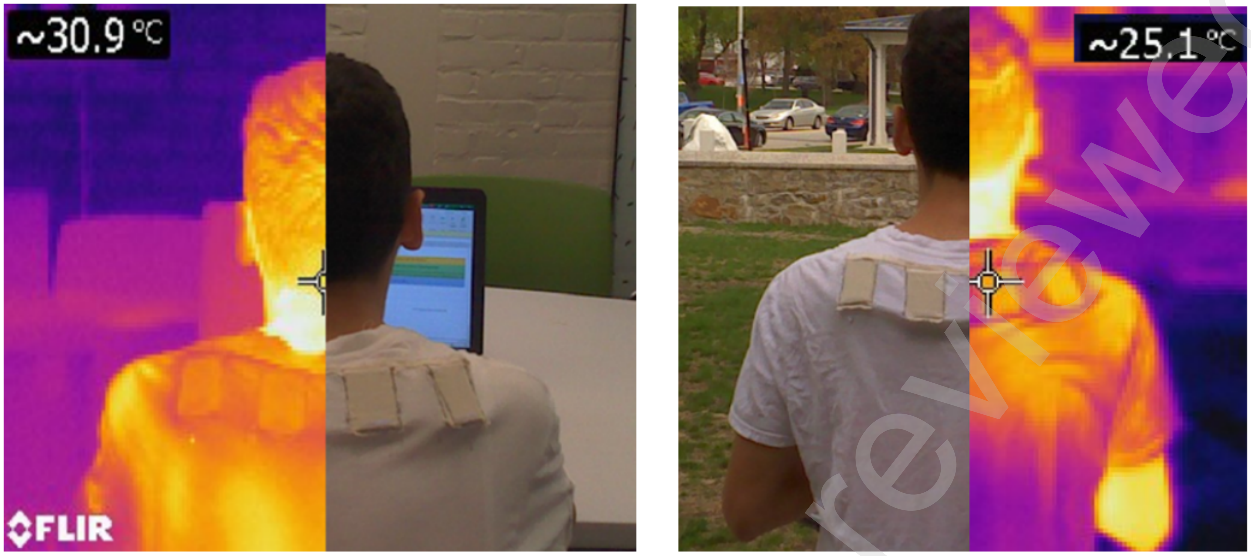
Abstract

The objective of this study is to investigate the effectiveness of a local wearable cooling solution in improving thermal comfort, emotional state, and cognitive performance. The study was conducted in an environmental room with air temperature of 31.5 ± 0.26 °C. Thirty participants performed six cognitive tasks while we periodically assessing their thermal experience locally where the cooling (Embr wave) was applied and for the whole body, as well as emotional states. The same protocol was applied to another thirty participants as the control group without local cooling. We also measured mean skin temperature and local skin temperature beneath the cooling device during the whole session. The results showed a significant drop in thermal sensation right after the application of the local cooling. Based on the ASHRAE 7-point scale for the overall thermal sensation vote, the local sensation dropped from 0.8 to -0.4 and the whole-body thermal sensation from 1.34 to 0.87. Over the 60 min of local cooling application, the local thermal sensation dropped from 0.98 to 0.04 and the whole-body thermal sensation dropped from 1.37 to 1.12. Furthermore, the local cooling group showed a significant drop in negative emotions and an increase in positive emotions compared to the control group. For cognitive performance, local cooling groups showed to be more inclined for risk taking for more rewards compared to the control group. The performance of other cognitive tests showed no significant difference between the two groups, even though attention, working memory and creativity were enhanced slightly but insignificantly.

Keywords

Wearable; Personal Comfort Systems; Upper-back cooling; Cognitive performance; Corrective power;

Graphical abstract



Highlights

- Proposed a low-energy cooling strategy to improve thermal comfort, emotion, and cognition
- Resulted in a significant drop in local and whole-body thermal sensation right after the cooling
- Positive emotions increased while negative emotions decreased.
- Positive effect of local cooling on risky decision making

1. Introduction

A major part of the energy supply is used for providing heating, ventilation, and air conditioning (HVAC) of buildings to achieve occupant's thermal comfort[1]–[3]. Despite these considerable efforts, many studies have found thermal discomfort in the built environment and its negative effect on productivity, emotions, and stress levels [4]–[7]. A study using very large dataset has shown that 42% of occupants showed dissatisfaction with their thermal environments, 39% satisfied [8], [9], and 19% neither satisfied nor dissatisfied. The satisfaction rate is far less than the ASHRAE standard target of satisfaction rate at 80% [8], [10]. One possible reason for the prevalence of thermal discomfort is while many buildings are designed to meet thermal comfort standards, these standards often overlook the varied individual preferences and needs of the occupants, which could contribute to the common issue of thermal discomfort [11]. Furthermore, in some cases, the indoor environment quality can be particularly poor due to the absence of air conditioning and ventilation systems, which can create significant effects in thermal discomfort, low productivity, and negative emotions [12]–[14]. As a promising solution to meet the challenge, personal comfort systems (PCS) have been suggested for low-energy solutions and for providing more dynamic application to address the individual variable needs [10].

PCS are devices that applies direct heating/ cooling to specific body parts [15]. It creates a personal environment to adhere to personal preference rather than changing the ambient environment for everyone, which often is impossible [10]. By delivering local heating and cooling stimuli, it induces an alliesthesia effect, a pleasant sensation that is generated when there is a correction of thermal imbalance in the body [16], increasing user satisfaction within different environmental settings [17]. This approach has been shown to be effective in achieving thermal comfort for individuals while also bringing energy usage down in various work environments [18], [19]. In addition, studies have shown that PCS can help improve the cognitive performance, emotions, and overall wellbeing of individuals, and potentially reduce energy consumption [20], [21].

PCSs offer a way to enhance thermal comfort and energy efficiency for building inhabitants. Various types of PCS have been studied in the past, including office chairs [17], [22]–[24], desk fans [25]–[28], vests [29], [30], and leg/foot warmer [31]–[33]. The devices have been found to be effective, yet they present certain limitations in terms of usability. For instance, office chairs, desk fans, and footwarmers require a stationary power supply or are restricted to stationary spaces like an office or a desk. Additionally, while cooling/heating vests have the benefit of being mobile, they are unwieldy and cumbersome. This research paper delves into the concept of a small wearable device that can produce cold stimuli for a localized cooling effect. We posit that using a small cooling device on a sensitive body region can be successful in achieving a cooling sensation without using substantial cooling energy.

The goal of this study is to investigate the effectiveness of a low-energy local cooling device on upper-back on the improvement of thermal comfort, emotional states, and cognitive performance in a warm environment. The study will shed light on energy-efficient solutions to provide cooling with the maximum practicality and flexibility.

2. Background on PCS studies

Personal comfort systems (PCS) are devices that enable individualized local cooling or heating by targeting specific body regions without affecting the overall environment. This allows individuals to personalize their thermal comfort and address any discomfort they may be experiencing [34]. Given the variability of interpersonal preference when it comes to thermal comfort, PCS can provide a controlled and customizable solution to improve thermal comfort, productivity, stress levels, and overall well-being. Additionally, using PCS can save energy by relaxing thermostat setpoints of spaces while maintaining the same level of comfort for occupants [18]. This technique offers a sustainable and optimal solution to address thermal discomfort and improve occupant satisfaction in buildings [10], [18], [35].

Various studies have investigated the effect of personal comfort systems on thermal comfort including chairs that incorporates cooling and heating [22]–[24], desk fans and jets offering various air flow rates and directions [25]–[28], leg/foot radiators [31]–[33], wearables modules [29], [30], [36], [37], and a combination of personal cooling and heating systems [38]–[42]. PCS has shown its capability to improve subjects' whole-body thermal comfort by targeting specific regions of the body [38], [40], [43]. It was also concluded that PCS can provide positive impacts on individuals' thermal comfort and sensation. Furthermore, PCS have the ability to make occupants' thermal comfort at more relaxed thermostat setpoints [32], [36], and can also address the variability of individuals and differences such as gender, age, and personal preference which is one of the main issues that are facing built environments [15], [36]. Overall, the use of PCS has the potential to significantly improve the thermal comfort and satisfaction of individuals in built environments and may be a useful tool for addressing the variability of thermal comfort needs among individuals.

Furthermore, PCS can deliver a rapid thermal stimulus by targeting specific body parts, leading to an immediate feeling of pleasantness of alliesthesia,. This pleasure response is triggered by the rapid heating or cooling of specific areas of the body through PCS [44]. The fast response of PCS in adjusting the temperature of regions of the body can lead to an immediate feeling of pleasantness, which gives them an advantage over traditional air conditioning systems in terms of delivering thermal pleasure [17], [45]. This is because traditional AC systems may take longer to adjust the temperature of a room or environment, whereas PCS can target specific body parts and provide a more immediate response.

Overall, the ability of PCS to deliver fast thermal stimuli and generate a positive alliesthesia response makes them an effective technology for regulating and enhancing thermal comfort.

In addition to thermal comfort, many studies have shown a strong relationship between indoor environment and work performance [14], [46], [47]. Recent studies have investigated the effect of PCS on productivity and cognitive performance. They have found that using PCS can decrease fatigue, increase motivation in individuals, and improve performance in simple cognition tasks (e.g., addition, multiplication) [26], [27], [48]. PCS also has the potential to increase concentration, and alertness for individuals' leading to better work performance [49]. It was also shown that it can decrease fatigue in individuals which can improve productivity and work performance [42]. Additionally, recent studies have shown the effect of PCS in increasing the performance of individuals on more complex cognitive functions (e.g., memory, reasoning, logical thinking) as well as simple calculation tasks, and found that applying local cooling can enhance cognition and performance [30], [50]–[52]. Overall, PCS can have a strong potential to improve cognition and work performance in a thermally uncomfortable environment.

Other studies investigated to what extent PCS can improve both thermal comfort and emotional. The use of PCS could improve emotional states or stop unpleasant feelings from developing if comfort is met by individual's preference [49]. However, the relationship between personal comfort systems (PCS) and emotions is still under studied.

Although the beneficial effect PCS offers to tackle energy consumption, thermal comfort, cognition, and emotional states, many PCS in the literature focus on furniture-based solutions (e.g., chairs, desk fans, leg/foot warmers) or relatively bulky and heavy vests to create enough cooling. Although those solutions might be effective in providing sufficient cooling, a vast implementation can be problematic. Alternatively, we in this study aims to explore a low-energy and small-size wearable cooling device that have little cooling capacity but may still be effective in elevating thermal comfort, emotional states, and cognition in a warm environment, if it can generate cool and dynamic stimuli on a sensitive body part.

Table 1 provides an overview of previous studies on personal cooling systems (PCS) and their impact on thermal comfort, and work performance. The table summarizes the key findings of these studies, highlighting the specific PCS that were investigated, the methods used, and outcomes measured, such as changes thermal sensation, thermal comfort and thermal acceptance, and any measured parameters related to work performance, such as productivity and cognitive performance.

Table 1. The effects of PCS on thermal comfort and cognitive performance in the literature

References	PCS solution	Thermal comfort	Work performance
[24]	Heating chair assisted with a leg warmer	Reduced cold sensation; Improved thermal comfort and acceptability	-
[22], [23]	Heated / cooled office chair	Strong influence on thermal sensation; Improve thermal comfort	-
[25]	Desk fans	Reduced warm sensation; Improved thermal comfort in different	-

		temperature settings	
[26]	Cooling jet	Improved thermal comfort	Improved speed of response in working memory
[27]	Air supply device	Improved thermal comfort	Improved working motivation
[28]	Heated seat and foot heater	Improved thermal sensation and comfort in cool environments	-
[32]	Footwarmers	Enabled lower thermostat setpoint in winter without effecting thermal comfort	-
[33]	Radiant leg warmer	Improves thermal comfort in mild cold and cold environment.	-
[36]	Wrist band wearable	Improved whole-body thermal sensation and comfort.	-
[37]	Neck cooling fans	Reduced local and overall thermal sensation	-
[29]	Pads overlayed on clothes	Local cooling of the torso can improve the overall thermal sensation and thermal comfort in a hot environment	-
[30]	Cool air towards breathing zone; Chest and back cooling	Decreased thermal sensation and improved thermal comfort	Increased simple and complex work performance
[38]	Heated / cooled chair; Heated / cooled wrist pad; Heated insole; Desk fan	Improved whole-body thermal comfort perception and thermal acceptability.	-
[40]	Heated chair; Heated desktop; Legwarmers	Increased thermal sensation Improved thermal comfort perception	-
[41]	Convection-heated chair; Under-desk radiant heating; Floor radiant heating panel; Air terminal device	Improved thermal comfort of individuals (need to increase heating effect for larger population satisfaction)	-
[42]	Radiant cooling desk and desk fan	Reduced warmth sensation and increased thermal comfort and extended thermal acceptability	Decreased fatigue
[48]	Desk fan	Perceived control over thermal environment showed affect of improved thermal comfort compared to no control	Improved addition and multiplication performance

[49]	Ventilation cooling seat; Water cooling seat	Reduced thermal sensation vote and improved thermal comfort	Increased concentration index
[50]	Desk fans; Heating desk; Heating mat	Improved thermal comfort in the mild cold to neutral environments	Increased effort and motivation (complex task); Increase alertness (simple task)

3. Material and methods

3.1 Wearable cooling device

Embr Wave modules developed by Embr Labs, Inc were used for local cooling in this study [53]. This battery-powered thermoelectric heat pump module provides precise temperature profiles against the skin. This device uses the Peltier effect, which involves the transfer of heat between two conductors when an electric current is passed through them, to generate dynamic waveforms of temperature against the skin. The device delivers periodic cooling to promote the perception of thermoreceptors with 20 s intervals. The device has a heating capacity of 32-42 °C and a cooling capacity of 25-30 °C, within a surface area of 6.25 cm^2. It is powered by approximately 2 W of power and weighs no more than 40 g [36], [54]. This solution offers a low-energy solution for providing warm or cool thermal sensations and allows users to customize their thermal comfort in a variety of settings, making it a flexible and adaptable solution for personal thermal comfort.

The control algorithm for the cooling mode employed can be described through two primary phases. Initially, the system operates in a cooling phase, wherein the Embr Wave initiates a cooling effect against the skin. If the heat sink reaches a predefined threshold when the device could not cool effectively due to the accumulated heat, safety mode is triggered which stops the cooling and it remains active until the temperature of the heat sink component decreases to a level where it is deemed safe to resume cooling. This dual-phase operation—cooling and safety—characterizes the Embr Wave's functionality within the PCS.

For this study, four Embr Wave modules were mounted to the upper-back of a T-shirt, serving as a wearable cooling device as shown in Figure 1. The cooling surfaces were ensured to make good contact with the skin. We chose the upper-back region due to the high effectiveness of cooling this region as shown by literature [55], [56]. Also, the neck has the highest heat dissipation rate compared to other body regions and features a complex network of blood vessels and a relatively large surface area, which facilitates efficient heat transfer [57]–[59]. Harnessing the neck's high heat dissipation rate in combination with the Embr Wave modules could potentially provide a more rapid and effective cooling sensation, enhancing thermal comfort and preference in individuals wearing the device. Therefore, this provides an effective way to increase local and overall thermal comfort and acceptability.

It should be noted that the Embr-wave on the upper back of the shirt in this study did not follow the original wrist-worn application, since the original application of the Embr wave is for the wrist. Furthermore, giving that the Embr waves were mounted inside a pocket of the T-shirt, the heat dissipation of the devices would be impacted by the clothing. Therefore, the performance of the Embr waves may be different from the original use on the wrist.

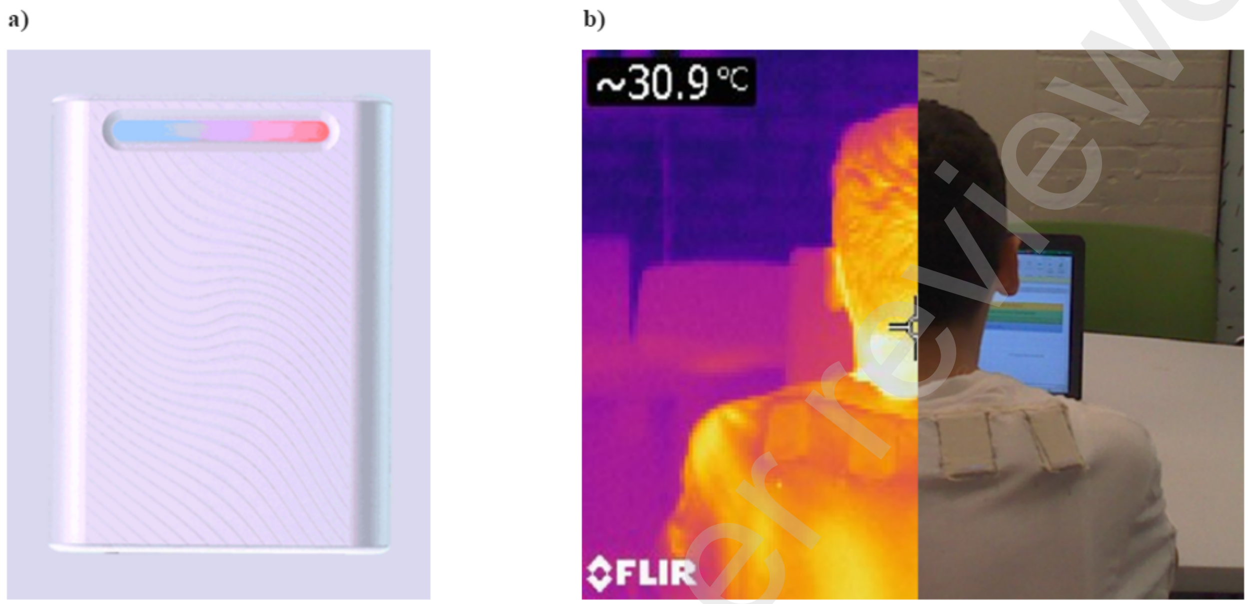


Figure 1. a). Embr Wave Device. b). A subject of the local cooling group in a test session with the wearable cooling device (total 4 Embr Wave devices). The inner surface of the device was directly contacted with skin by tailoring the T-shirt.

3.2 Environmental chamber

The experiment was conducted in a climate chamber at the Worcester Polytechnic Institute (WPI). The climate chamber has a floor area of approximately 6 m × 2 m. The chamber was connected to an HVAC system that delivers the desired air condition to the room.

The experiment was carried out from November 2021 to February 2022. The environmental parameters were maintained at a steady level with air temperature at 31.5 ± 0.26 °C, relative humidity at 30 ± 5.30 %, indoor CO_2 level at 910 ± 134 ppm, vertical luminance at 303 ± 16 lux, and noise level at 63.33 ± 2.69 dB. These conditions were chosen to simulate summer conditions with no air conditioning. The detailed experimental conditions monitored in the study can be found in Appendix A1.

3.3 Subjects

Sixty university students (35 males and 25 females) participated in the experiment. The participants were recruited through email invitations and flyers around the campus. The participants were randomly split into the control and experimental group with the same size. Thirty participants were tested for local cooling conditions using the wearable cooling strategy, while the other thirty had no local cooling attached as the control group. A summary of the participants' general information and for the two groups can be found in Appendix A2. All subjects were instructed to avoid alcohol, caffeine, nicotine, and intense physical activities the day of the experiment. Each participant was compensated $15 an hour and provided an informed consent before starting the experiment.

All subjects wore the same level of clothing during the experiment, which consisted of underwear, t-shirt, shorts, socks, and walking shoes. These clothing were chosen to simulate summer clothing. The clothing insulation of the garments was estimated to be 0.36 (including 0.07 clo from the chair). The t-shirt, shorts and shoes were provided to all subjects by the experimenters, other garments were brought by the subjects. During the experiments, subjects were working on a computer throughout the experiment, which gives an estimate metabolic rate of 1.1 met for this activity.

3.4 Questionnaires

The questionnaires contained an overall and local thermal evaluation, an emotional evaluation, and a performance evaluation described in this section. We deployed all the questionnaires using Inquisit v6 (Millisecond®), an experimental application used for designing and administering psychological experiments and measures. The description of the surveys can be found in Appendix A3.

3.4.1 Whole-body and local thermal assessment

The questionnaire used in this study consisted of two parts: an overall thermal evaluation and a local thermal evaluation. The local thermal evaluation specifically focused on the upper-back region of the body where local cooling was applied. Both surveys targeted "Right-now" thermal sensation, thermal comfort, thermal acceptability, and thermal preference. All thermal questionnaires followed the concept of the American Society of Heating, Refrigerating, and Air Conditioning (ASHRAE) 7-point scale (-3 to +3). The participants answered a continuous scale for thermal sensation ranging from *Hot (+3) to Cold (-3)*. For Thermal comfort and acceptability, a continuous scale was used raging from *Clearly Uncomfortable (-3)* to *Clearly Comfortable (+3)*, and from *Clearly Unacceptable (-3)* to *Clearly Acceptable* (+3) respectively, with an exclusion of the neutral value *(0)*. For thermal preference, scales ranged from *Warmer (+3)* to *Cooler (-3)* that was modified based on ASHRAE Standard 55 [2]. The explanation to each scale was made through an explanatory video at the start of the experiment so that all subjects could have the same understanding of the scales.

3.4.2. Emotional states

To assess the emotional state of the participants, we used the Positive and Negative Affect Schedule – Short Term (PANAS-SF). It is a subjective questionnaire that rates subjects' level of positive and negative emotional states [60]. The questionnaire is composed of 5 positive emotional subscales (determined, attentive, alert, inspired and active), and 5 negative subscales (afraid, nervous, upset, ashamed, hostile). Each affect is scaled using a 5-point Likert Scale ranging from 1 = "Not at all" to 5 = "Extremely". The PANAS-SF was found to be adequate, reliable, and efficient in capturing the positive and negative affect of an individual as a short metric evaluation [61].

3.4.3 Task load

The NASA Task Load Index (NASA-TLX) was used to determine cognitive task load of the participants. This survey relies on a multi-dimensional scoring procedure, incorporating six items including mental demand, physical demand, temporal demand, performance, effort, and frustration. Each item is scored on a continuous scale ranging from 0 = "low" to 7 = "high" [62].

3.5 Cognitive performance tests

To assess the effect of local cooling on cognitive performance between the two groups, we used 6 module tests deployed in Inquisit v6 Software (Millisecond®). The tests used were the *Token Task* to assess the working memory [63], the *Stroop Color Task* to assess response inhibition [64], the *Spatial Processing Task* to assess short term memory [65], the *Balloon Analogue Risk Task* (BART) to assess risk propensity [66], the *AX-CPT Task* to assess attention [67], and the *Alternative User Task* (AUT) to assess creativity [68]. The selection of the cognitive tests was based on s previous study that showed which tests can be used to assess desired cognitive function [69]. All cognitive tasks took an average period of 6 min each to complete. A description and screenshots of the cognitive tasks can be found in Appendix A4.

3.6 Skin temperature measurements

The skin temperature of the subjects was measured during the experiment using iButton® Sensors (model DS1922L-F50, Maxim Integrated, San Jose, CA) with a sampling interval of 1 min, which were attached at four sites (right calf, right thigh, right arm, and left chest) as illustrated in Figure 2. The upper-back temperature was also measured using a fast-responsive temperature sensor (g.tec medical engineering GmbH, Austria), with a sampling interval of 0.004 s (250 Hz) and accuracy of 0.2 °C. The sensors were attached to the skin using a thin medical tape and placed under the cooling module to capture the temperature of the cooled area surface. The mean skin temperature was calculated according to Equation 1 with local skin temperature obtained from the four iButton® sensors [70].

$$T_{mean} = 0.2 * (T_{calf} + T_{thigh}) + 0.3\ (T_{arm} + T_{chest}) \qquad \text{(Eq. 1)}$$

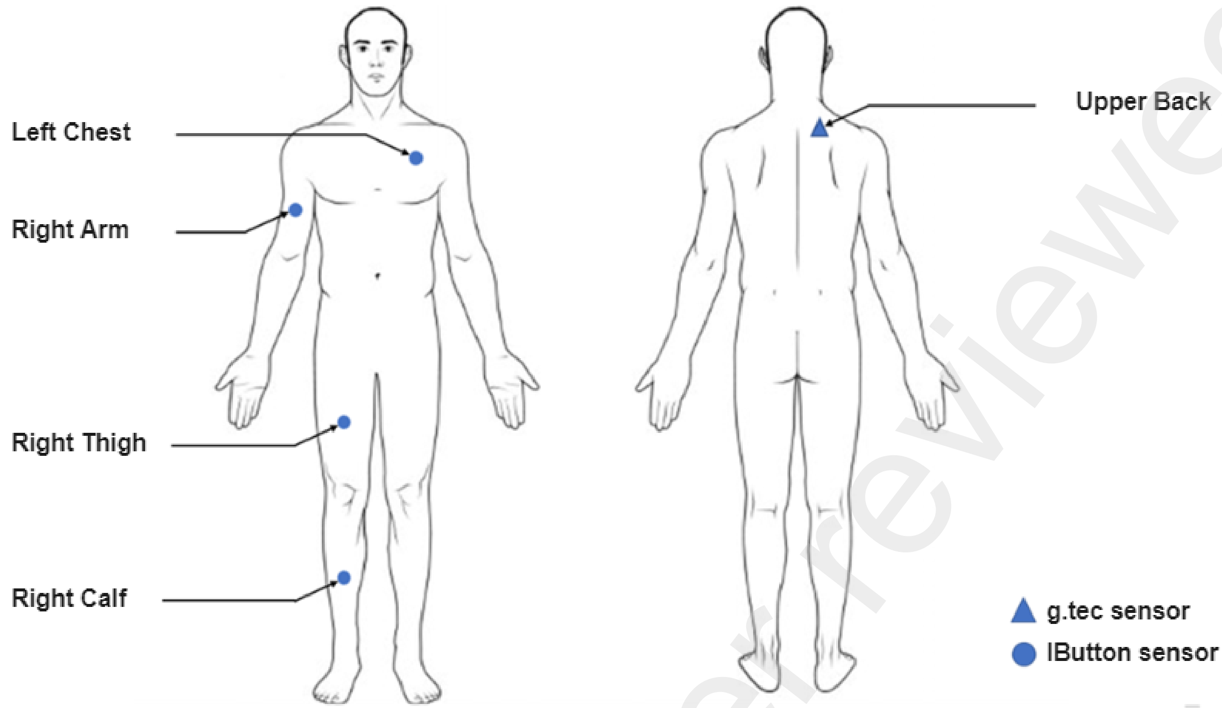


Figure 2. Temperature sensor positions. Four iButton® sensors (blue circles) were used to measure mean skin temperature every 1 min, while one g.tec skin temperature sensor (blue triangle) recorded skin temperature on the upper-back at the frequency of 250 Hz. Appendix A5 depicts the two sensor types.

3.7 Protocol

Figure 3 describes the experimental procedure for the two groups. Each experimental session lasted for an average of 88 min. During the session, subjects spent a 30 min thermal adaptation phase when they watched a video explaining the different questionnaires and tasks before the formal test. This allowed them to become familiar with the tasks and questionnaires and gave them time to adjust to the testing environment. Following the adaptation phase, participants were asked to fill out the thermal evaluation and emotion assessment surveys. For the experimental group, after the initial assessment was taken, the wearable thermoelectric modules were then mounted to their t-shirt and turned on. Once the cooling modules were activated, the experimental group were immediately asked to answer a second thermal and emotional evaluation surveys. By utilizing this measure, we were able to assess any transient shifts in both overall and localized thermal perception, which could signify the presence of temporal alliesthesia [71], as well as the influence of emotions during the application of local cooling. Participants were then asked to take cognition tasks and questionnaires. The cognitive tasks were chosen randomly for both conditions for participants. Following the last thermal and emotional questionnaires, subjects were asked to fill out a NASA-TLX performance evaluation questionnaire at the end of the visit.

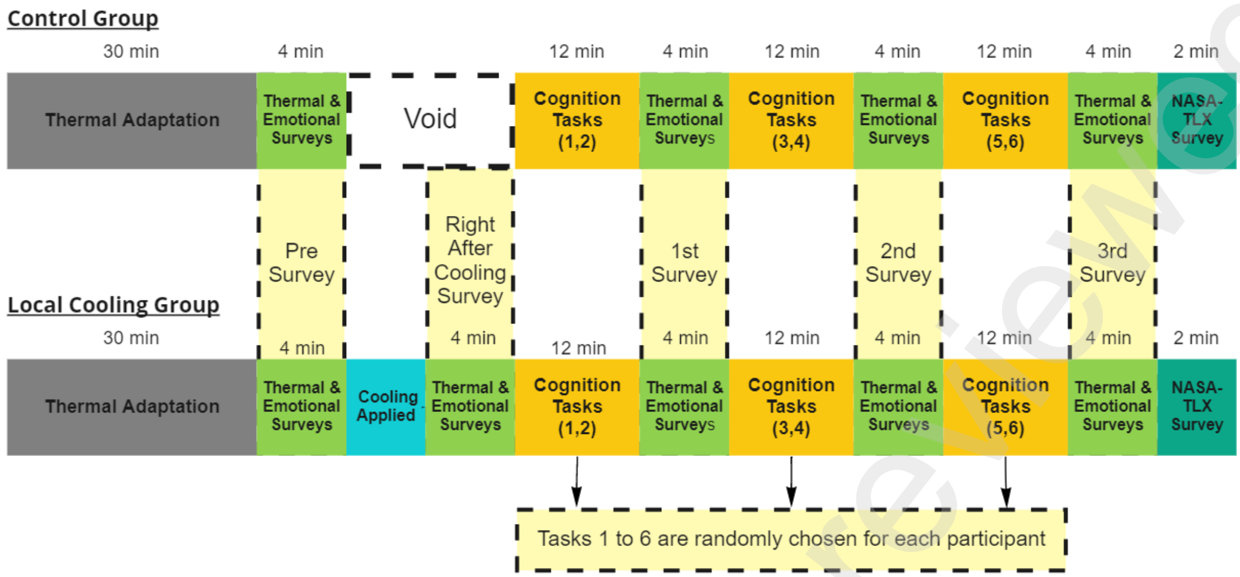


Figure 3. Experimental protocol for the control and local cooling groups

3.8 Statistical analysis

Numerical results were presented as mean ± standard deviation (SD) in the paper. Furthermore, all statistical analyses were conducted using Python's library *SciPy* [72]. First, the *Shapiro-Wilk* normality test was used to verify data normality. Normally distributed data were subject to *t-test.* Otherwise, the *Mann-Whitney U test* was used as a non-parametric test for non-normally distributed data. All results were considered statistically significant when $p < 0.05$. The symbol "*" indicates a statistical significance of $p < 0.05$, whereas "**" symbolizes $p < 0.01$ which is very significant, and "***" symbolizes $p < 0.001$ which is highly significant. Furthermore, *Cohen's d* values (noted as *d*) were used to assess the practical significance of the effect size between the different means of the data [73]. The thresholds by which the effect size was interpreted were $|d| < 0.147$ "negligible", $|d| < 0.33$ "small", $|d| < 0.474$ "medium, otherwise "large".

4. Results

Responses to questionnaires on local and whole-body thermal evaluation were analyzed in addition to the skin temperature data. Then we present the comparison of emotion and cognitive performance between the two groups in this section. Skin temperature was analyzed based on a 5 min time window to compare the difference of temporal skin temperature between the two groups.

In our data analysis, we organized the collected data into distinct time windows, each corresponding to specific durations when participants completed assessment surveys. To illustrate, a 5-minute time window captured the initial survey taken by both groups at the beginning of the experiment. Subsequently, a 10-minute time window was designated for the survey that the local cooling group completed immediately after the application of local cooling. This allowed us to capture any potential changes in effects due to the cooling. For the control group, within the 10-minute window, we assumed that the responses related to thermal evaluation remained consistent with those from the initial 5-minute window. Additionally, we employed 25-minute, 40-minute, and 65-minute time windows to encompass the assessment surveys conducted by both groups after each period of cognitive task engagement.

4.1 Thermal sensation

4.1.1 Whole-body thermal sensation

Figure 4 displays the whole-body thermal sensation (WBTS) significantly dropped right after the local cooling was applied (*p = 0.02*) at 10 min. In particular, the median WBTS vote dropped by 0.47 scale before the local cooling was applied (*1.34* ± *0.61*) and after the application (*0.87* ± *0.86*). There was no statistical significance after the first cognitive task period (at 25 min). However, we observed a statistically significant (*p =0.02*) reduction in WBTS after the second cognitive task period (40 min). The last cognitive task period (65 min) showed no significant change between the two experimental groups. These results show that the WBTS was affected by the local cooling, but the effects varied temporally. In addition, we aggregated all the WBTS votes across the entire session for both groups. The statistical analysis indicated a significant difference (*p = 0.03*) between the WBTS of the local cooling group (*1.12* ± *0.90*) and that of the control group (*1.37* ± *0.72*), suggesting a positive effect of the local cooling device on the whole-body thermal sensation.

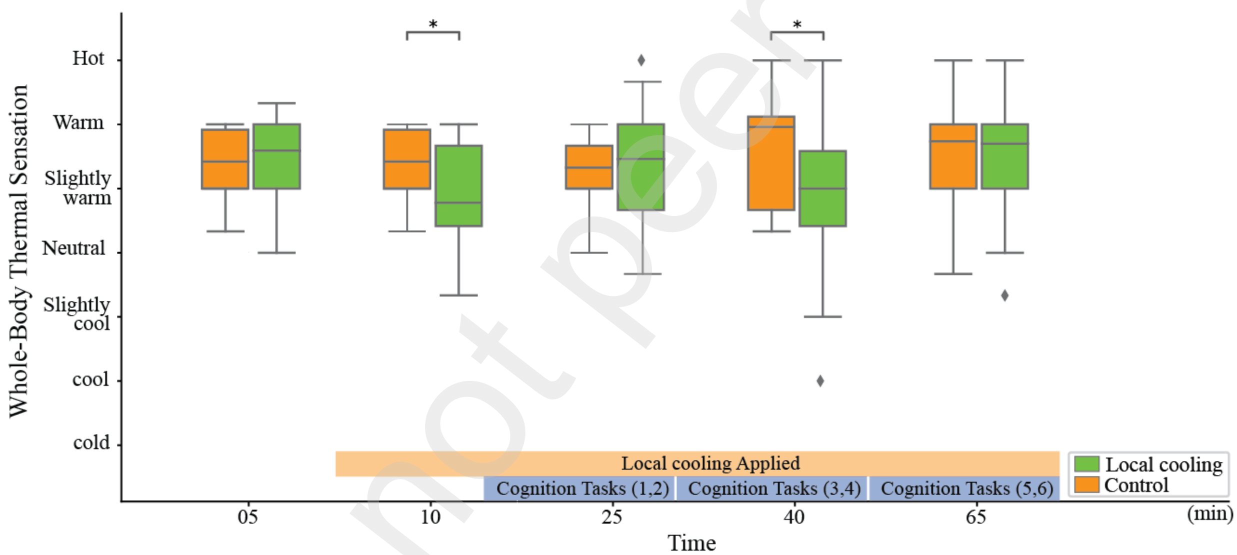


Figure 4. Comparison of the whole-body thermal sensation between the two groups

4.1.2 Upper-back thermal sensation

The upper-back thermal sensation (UBTS) exhibited a significant difference between the local cooling group and the control group for all survey periods. Figure 5 illustrates a substantial reduction (*p = 0.001*) in UBTS for the local cooling group compared to the control group immediately after the application of the local cooling device. Throughout the session, the control group consistently reported a median perception of "slightly warm" on the upper back, whereas the local cooling group experienced median sensations ranging from "neutral" to "slightly cool." Although the local cooling effectively reduced the thermal sensation at the upper back, the cooling effects gradually attenuated with time, as indicated in Figure 5. This attenuation could be explained by the upper-back skin temperature increase in the last 35 min due to the safety mode of the Embr Wave, as explained in Figure 10. Analysis of all collected votes throughout the session revealed a significant decrease (*p = 0.001*) in UBTS from *0.98* ± *0.73* for the control group to *0.04* ± *1.34* for the local cooling group.

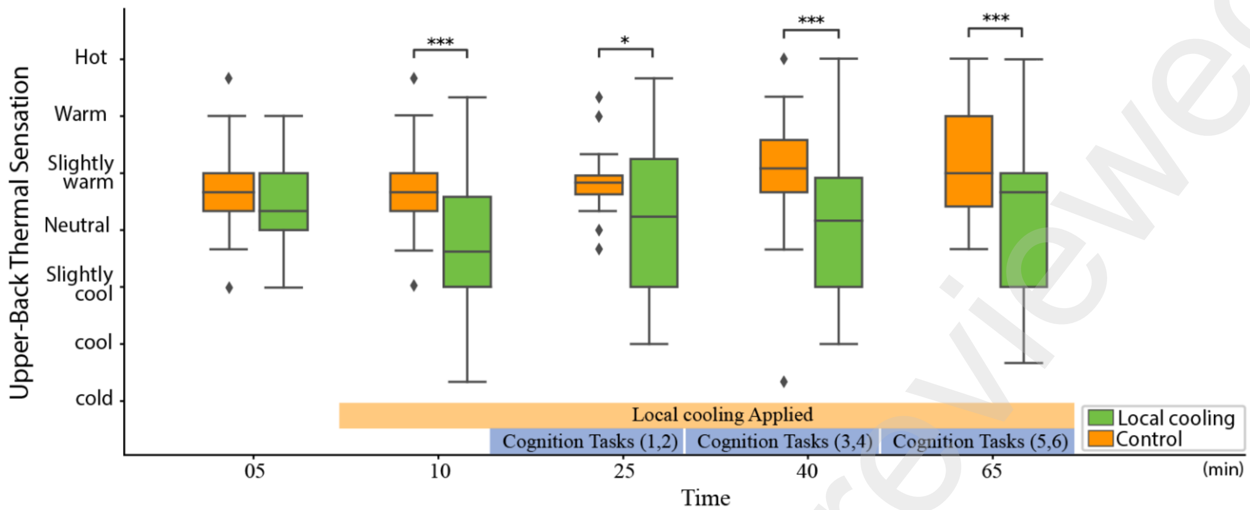


Figure 5. Comparison of the upper-back thermal sensation between the two groups.

4.2 Thermal comfort, acceptability, and preference

In general, the low power cooling device was not able to significantly alter thermal comfort, acceptability or preference regarding either whole body or upper-back region. Nevertheless, the quantitative comparison between the two groups still sheds light on the effectiveness of the cooling device in enhancing thermal experience in a warm environment. This section describes the detailed findings on the three thermal evaluation indexes.

Figure 6a displays the comparison of whole-body thermal comfort (WBTC) and upper-back thermal comfort (UBTC) of both groups. WBTC was slightly improved from *0.10 ± 1.04* to *0.21 ± 1.16* immediately but insignificantly after the local cooling was applied for the cooling group. Throughout the entire session, the control group experienced slight thermal discomfort *(-0.14 ± 1.39)* compared to the local cooling group with the thermal comfort level of *0.01 ± 1.38.* Appendix Table A6 describes the detailed comfort levels and statistical test results.

Figure 6b suggests no statistically significant difference in UBTC between the two groups. However, upon the application of the local cooling device, participants experienced a decrease in thermal comfort from *0.59 ± 1.11* to *0.20 ± 1.22*, possibly due to the sudden cooling "shock" caused by the device. This observation is supported by the low thermal sensation (-0.40 ± 1.37) reported at the upper back. Furthermore, the UBTC for both groups declined over time, indicating the influence of exposure duration on thermal comfort. Throughout the entire session, the local cooling device slightly improved local comfort at the upper back, although this improvement did not reach statistical significance.

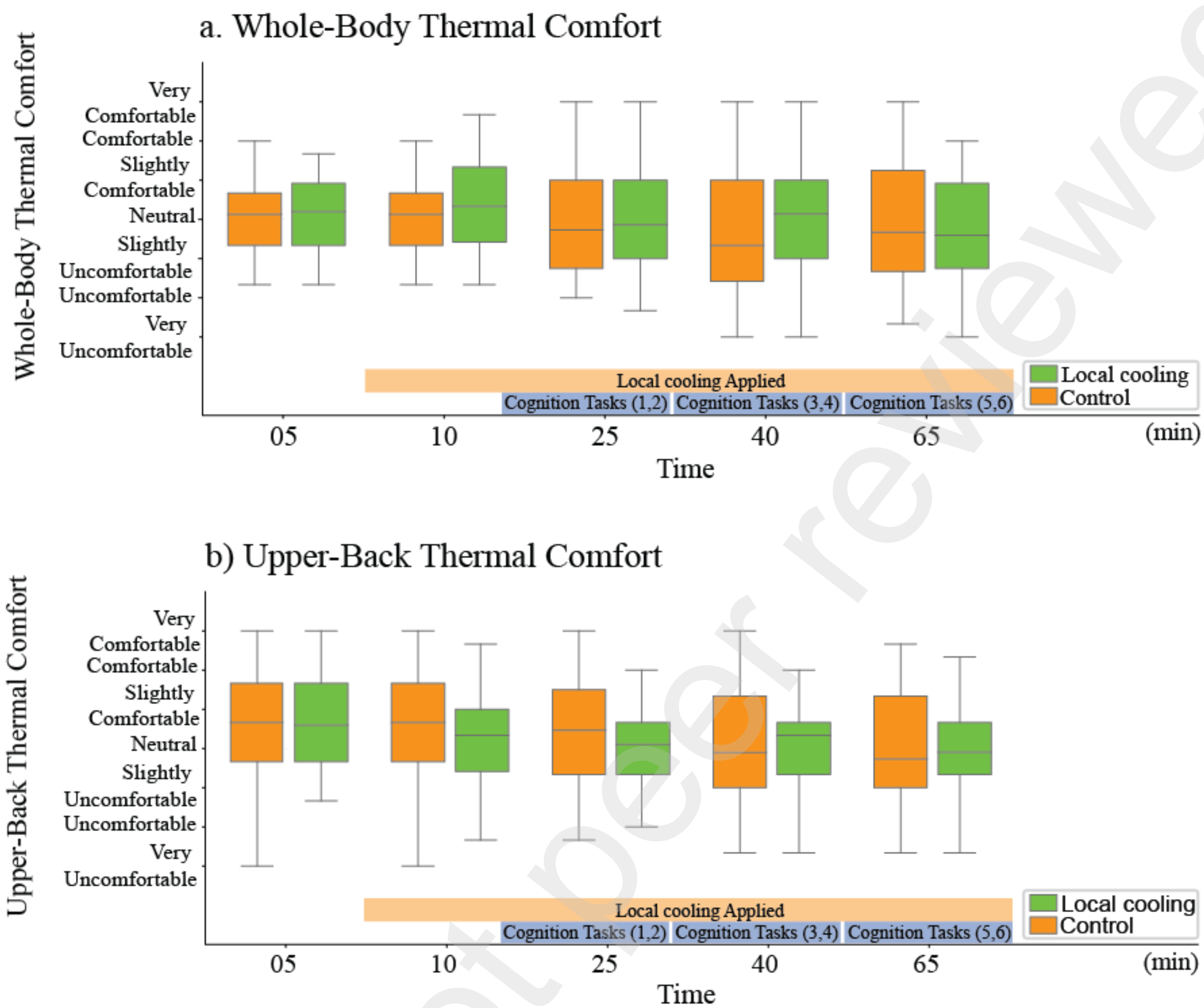


Figure 6. Whole-body and upper-back thermal comfort

Furthermore, we did not observe any significant improvement in overall or local thermal acceptability after using the wearable cooling device (Figure 7). The average whole-body thermal acceptability was *0.24* ± *1.39* for the control group and *0.40* ± *0.39* for the local cooling group. These results indicate that participants had a slightly higher acceptable perception of the thermal environment with the local cooling. The upper-back thermal acceptability was similar between both groups, with a statistical level of approximately *0.5*. Moreover, participants in both groups reported a decrease in thermal acceptability over time, both overall and locally. In particular, Appendix Table A6 shows that the whole-body and upper-back thermal acceptability dropped roughly *0.4-0.8* from the start to the end of the test session.

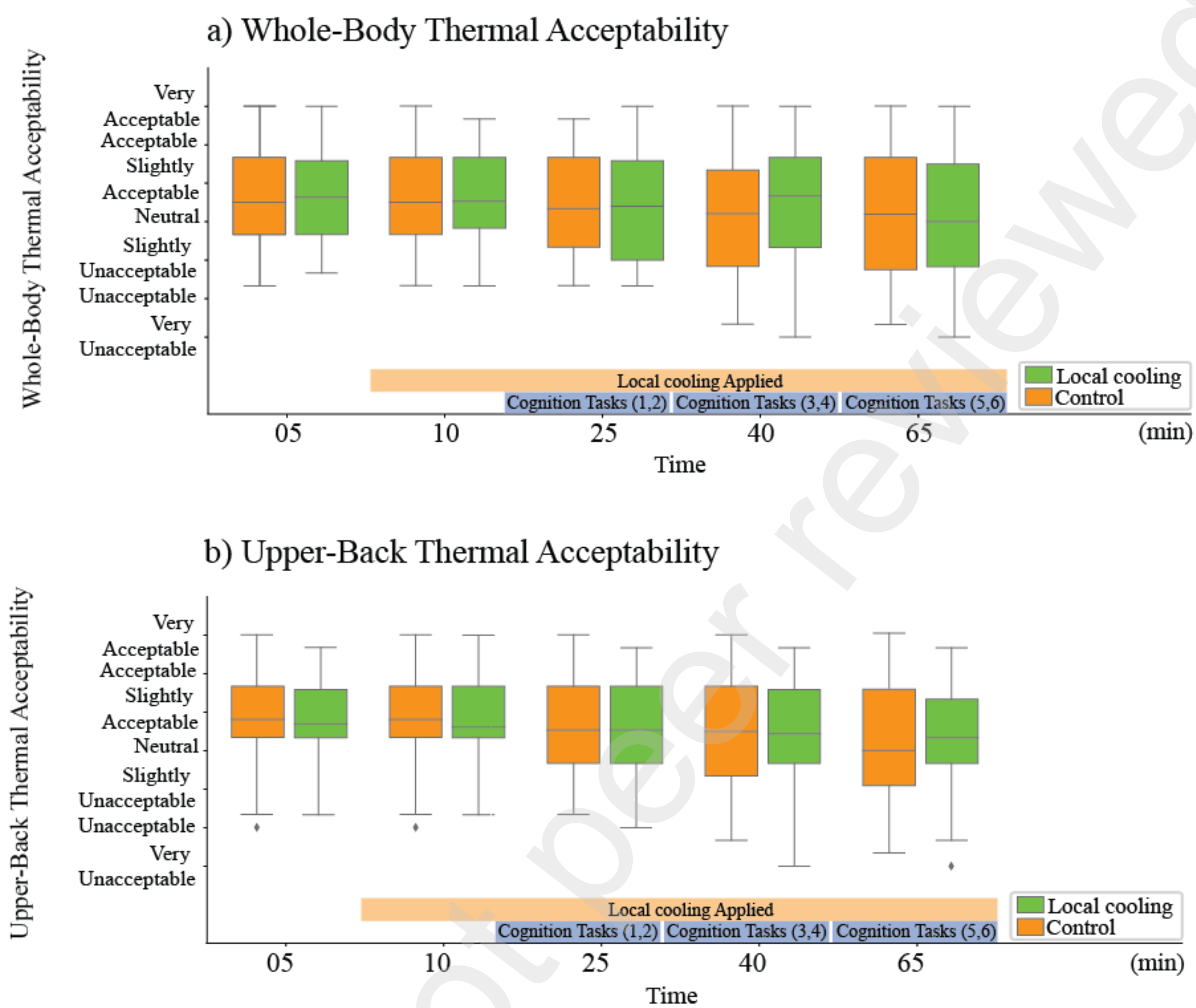


Figure 7. Whole-body and upper-back thermal acceptability

At the warm environment, participants on average indicated a preference for cooling as displayed in Figure 8. The average thermal preference across the entire test session was approximately -1.1 for the whole body and -0.9 for the upper back region. Participants without the local cooing device showed a stronger but not significantly preference of cooling compared to the other group. The results imply that the low power cooling device was not able to alter participants' thermal preference significantly.

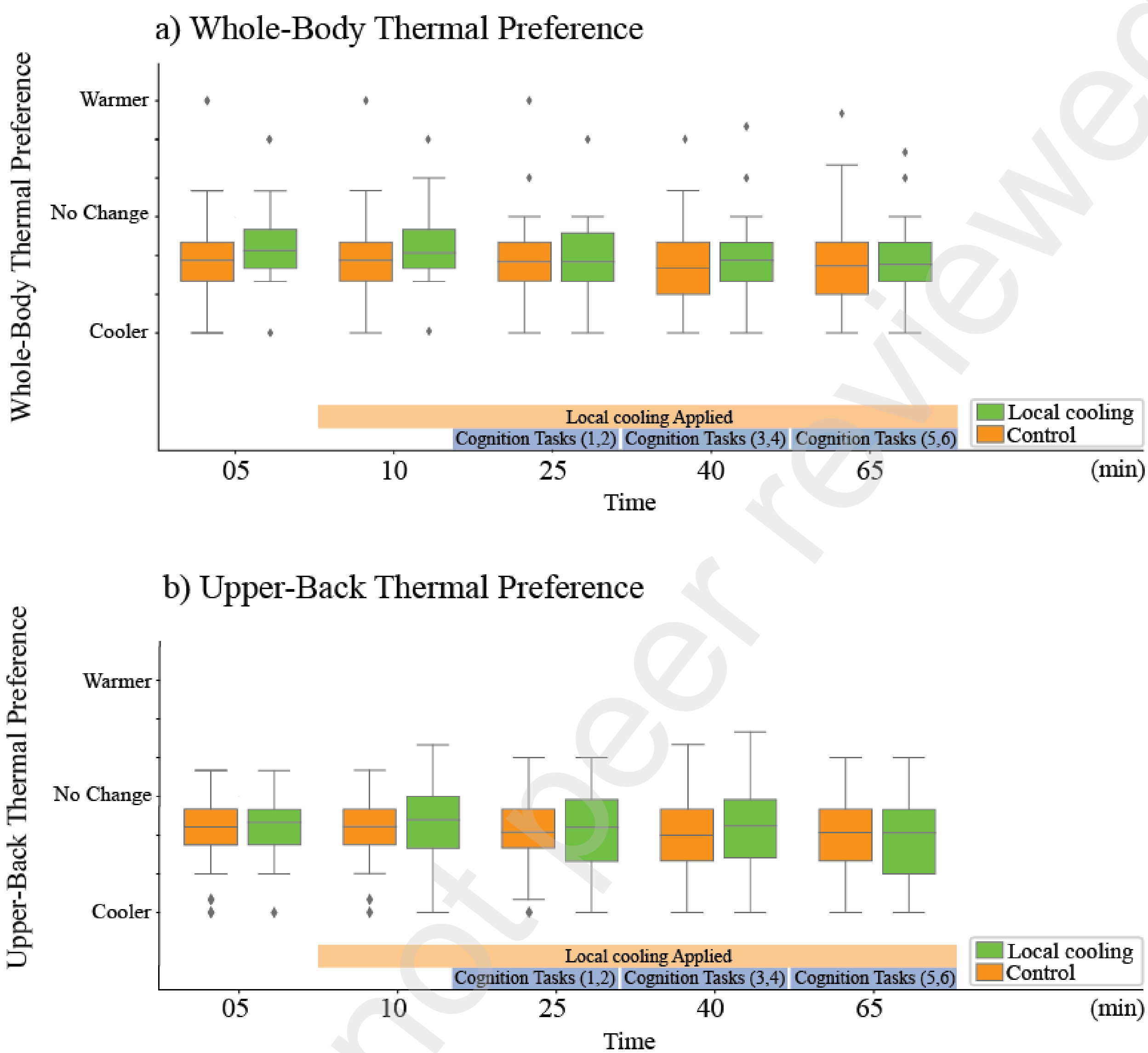


Figure 8. Whole-body and upper-back thermal preference

4.5 Skin temperature

4.5.1 Mean skin temperature

Figure 9a illustrates the temporal changes in mean skin temperature for both groups, with the shades representing the standard deviation of temperature within each group. The measurements reveal substantial individual variations in skin temperature. Furthermore, the average skin temperature gradually increased from 34 °C to 34.5 °C over the 88 min session, indicating a prolonged period required to reach a stable condition. Appendix A6.2 displays the skin temperature at specific body locations, revealing that the temperatures of the hands and calves reached a steady state earlier than those of the thighs and chest. Figure 6b presents a comparison of the mean skin temperature between the two groups within a 5 min time window. The statistical tests indicate no significant difference between the groups. Consequently, the local cooling applied to the upper-back region did not effectively reduce the mean skin temperature.

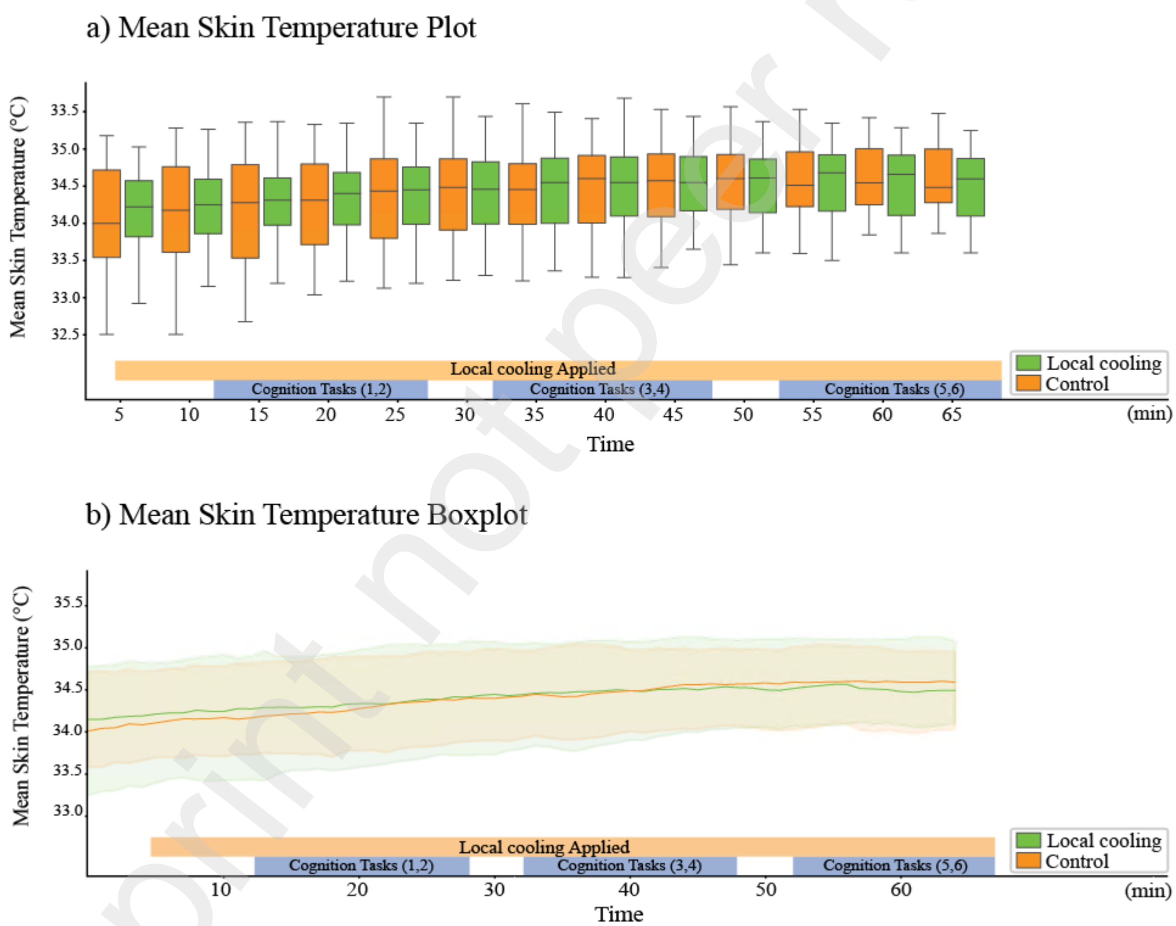


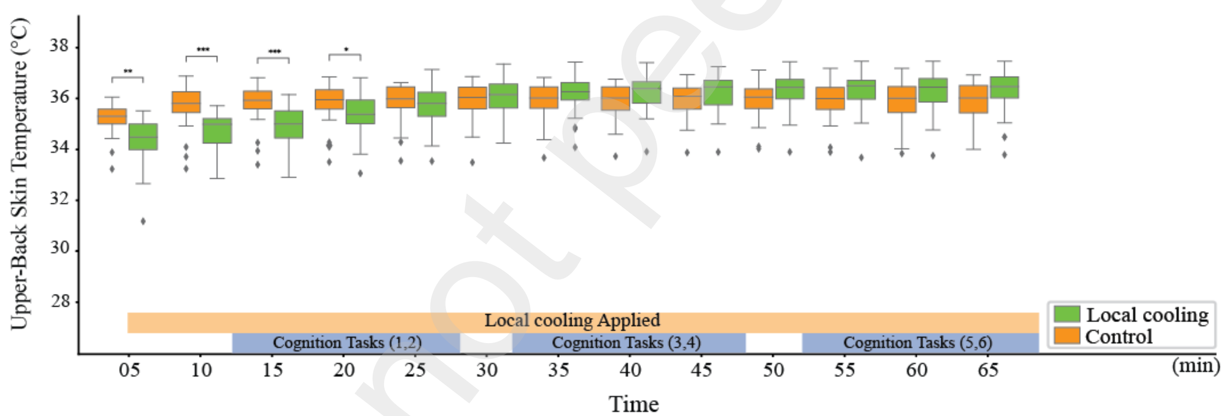
Figure 9. Mean skin temperature of the two groups ; a) The temporal variation ; b) Temperature comparison between two groups

4.5.2 Upper-back skin temperature

After the application of the cooling device, the upper-back skin temperature immediately decreased by approximately 0.5 °C within 5 min, as shown in Figure 10a. However, the local skin temperature gradually started to rise afterward, reaching a similar level compared to the control group within 15 minutes. The micro-level temperature fluctuations were caused by the dynamic cooling waveform. Figure 10b illustrates the comparison of skin temperature between the two groups at 5 min intervals. Significant differences were observed between the two groups after the application of local cooling, which persisted for approximately 20 minutes (from 5 min to 20 min). After that, no significant difference was observed between the two groups.

This observation can be interpreted by the control mechanic functionality as explained in the methodology where the Embr wave cooling mode is based on two control phases which ensure the functionality of the Embr wave cooling while safely dissipating heat when the device is too hot. As a result, following the completion of the initial 20-minute cooling phase, the activated safety mode and the complex interplay of heat dissipation mechanisms could potentially give rise to fluctuations in both the strength and duration of the cooling sensation. In other words, the cooling experience after the initial 20 minutes may not remain uniform, owing to the interplay between the safety mode's intervention and the intricate process by which heat dissipates within the unique framework of the proposed PCS system. This interplay introduces an additional layer of complexity that may introduce variations in how users perceive the cooling effect beyond the initial cooling period.

a) Upper-Back Skin Temperature Plot



b) Upper-Back Skin Temperature Boxplot

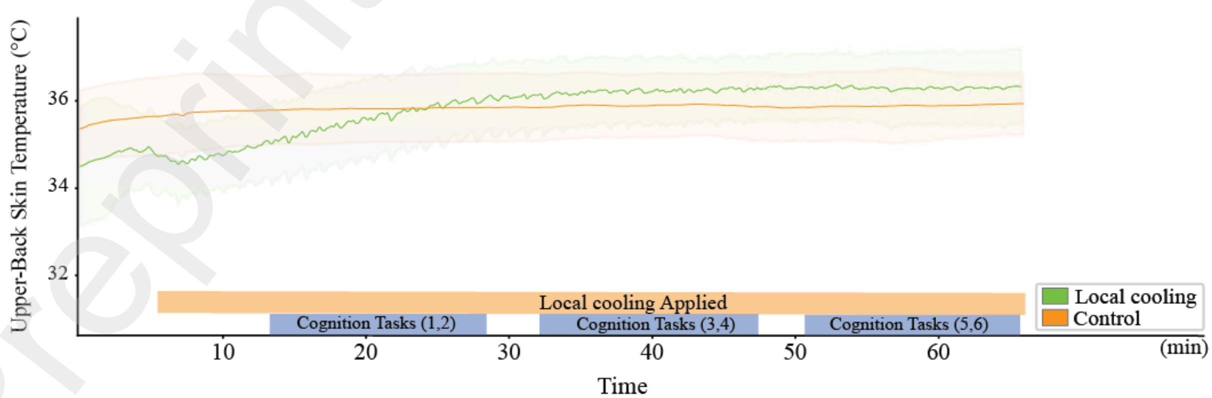


Figure *10*. Local skin temperature at the upper back region of the two groups; a) The temporal variation ; b) Temperature comparison between two groups

4.6. Emotions

We compared the 10 positive and negative emotions assessed by the PANAS-SF, as well as the overall positive and negative emotional states by calculating the mean of the 5 emotions in each category. Table 2 presents that the local cooling group reported a significant increase in attentiveness compared to the control group without the local cooling device ($p = 0.045$), with a small effect size (Cohen's $d = 0.219$). Furthermore, the device has demonstrated a moderate to large effect size in reducing negative emotions such as feeling afraid ($p = 0.006$), upset ($p = 0.0004$), hostile ($p = 0.001$), along with the overall negative emotional state ($p = 0.0018$). The results show that local cooling at the upper back can improve the emotional state of individuals by enhancing positive emotions and particularly reducing negative emotions.

Table 2. PANAS-SF Statistical Analysis Results

Emotional State		Mean ± SD		p-value	Cohen's *d*
		Control Group	**Local Cooling Group**		
Positive Emotions	Determined	3.30 ± 1.21	3.36 ± 1.08	0.34†	0.056
	Attentive	3.19 ± 1.22	3.46 ± 1.20	0.045†*	0.219
	Alert	3.09 ± 1.23	3.29 ± 1.26	0.09†	0.166
	Inspired	2.61 ± 1.28	2.71 ± 1.35	0.26†	0.079
	Active	2.93 ± 1.25A	2.28 ± 1.41	0.28†	-0.070
	Overall Positive Emotion	3.024 ± 1.06	3.134 ± 1.14	0.23†	0.100
Negative Emotions	Afraid	1.26 ± 0.59	1.08 ± 0.31	0.006† **	-0.360
	Nervous	1.53 ± 0.74	1.43 ± 0.77	0.061†	-0.137
	Upset	1.43 ± 0.72	1.14 ± 0.35	0.0004† ***	-0.503
	Ashamed	1.09 ± 0.72	1.07 ± 0.26	0.27†	-0.078
	Hostile	1.25 ± 0.55	1.162 ± 0.236	0.001† **	-0.410
	Overall Negative Emotion	1.32 ± 0.40	1.162 ± 0.24	0.0018† **	-0.462

†: Mann-Whitney non-parametric results, while remaining p values refers to the *t-test* parametric results

4.7. Cognitive performance and task load

Table 3 summarizes the comparisons of the cognitive performance across the six tasks. The only statistically significant difference observed was “Adjusted Total Pump Count” in BART used to assess risk taking. The local cooling group exhibited a significantly higher adjusted total pump count of *814.93* ± *227.94* compared to the control group with *706.3* ± *129.93*, indicating an increase of 7.14 %. The finding suggests that participants with the local cooling device were inclined to take higher risks. The possible explanation is that the local cooling device reduced thermal discomfort, leading participants to be more engaged in performing the task longer. Furthermore, when it comes to other cognitive tests such as memory, attention, and creativity, the local cooling device did not show significant improvements in performance. Despite this, it is worth noting that there were observed increases in creativity (4.06 %), attention (1.12 %), working memory (0.76 %), and response inhibition (2.13 %) for the cooling group, albeit not statistically significant. These findings indicate a potential trend towards improved cognitive functions, although the effect may not be strong enough to reach statistical significance in this study.

In summary the local cooling device in this study had a noticeable impact on risk-taking behavior. Although not significant, the local cooling did enhance performance in other cognitive tests or reduce the perceived task load. The observed increases in creativity, attention, working memory, and response inhibition for the experimental group indicate a potential positive effect of the local cooling device on these cognitive functions, but further research is necessary to confirm these findings and establish their statistical significance.

Table 3: Statistical Analysis summary of the cognitive tasks for the two groups

Cognitive Test	Cognition Function	Evaluation Metric	Mean ± SD		P-value	Cohen's d
			Control Group	Local Cooling Group		
Token Task	Working Memory	Percent accuracy	92.53 ± 3.70	93.23 ± 3.50	0.45	-0.194
Stroop Color Task	Response Inhibition (Reaction Time)	Proportion Correct	0.94 ± 0.04	0.96 ± 0.03	0.17†	-0.333
		Reaction Time (ms)	0.92 ± 0.089	0.93 ± 0.07	0.45†	-0.121
Spatial Processing Task	Short Term Memory	Proportion correct (0-deg)	0.47 ± 0.17	0.43 ± 0.18	0.41	0.214
		Proportion correct (90-deg)	0.79 ± 0.17	0.77 ± 0.164	0.355†	0.182
		Proportion correct (180-deg)	0.43 ± 0.15	0.436 ± 0.17	0.409†	-0.015
		Reaction time (ms)	1289.12 ± 272	1199.17 ± 266.7	0.1†	0.334
BART Balloon Task	Risk Taking	Total explosions	12.13 ± 4.32	10.53 ± 3.80	0.13	0.393
		Adjusted Total Pump Count	706.3 ± 129.93	814.93 ± 227.94	**0.0027****	-0.586
		Average adjusted Pump Count	42.19 ± 13.4	43.69 ± 13.70	0.67	-0.111
AX-CPT Task	Attention	Proportion correct	0.89 ± 0.23	0.90 ± 0.14	0.19†	0.258
		Reaction time (ms)	444.96 ± 103.02	406.8 ± 92.35	0.18†	-0.390
Alternative User Task	Creativity	Average Score	3.20 ± 0.91	3.33 ± 0.77	0.39†	0.155

†: Mann-Whitney non-parametric results, while rest refers to the T-test results

5. Discussion

This section is divided into five main sections. The first section examines the corrective power of the local cooling device to shift the thermal sensation of users towards a neutral state. Second, the effects of local cooling on cognitive performance was summarized by comparing this study with the literature. Third, we conducted further statistical exploration on whether the local cooling device has improved thermal experience, emotion, and cognition for female and male participants separately. Lastly, we hypothesize that the local cooling device might be more effective for participants who felt warmer than others at the same air temperature. Hence, additional statistical tests were performed by considering different initial thermal sensation levels at the beginning of the experimental session.

5.1 Corrective Power (CP)

In this section, we investigate the effectiveness of the local cooling device by calculating the corrective power (CP), which can be defined as the difference of thermal sensation between the control and local cooling groups. This calculation (Equation 2) represents the ability of the local cooling PCS to shift the thermal sensation of users toward a neutral state in any non-neutral environment [10].

$$CP = \frac{TS_{local\ cooling} - TS_{control}}{G} \quad (2)$$

$TS_{local\ cooling}$is the thermal sensation (whole-body or local) reported by the local cooling group, while $TS_{control}$ is for the control group. We chose a value of $G = 0.33\ sensation\ unit\ /°C$ following our previous study [36]. G represents equivalent thermal sensation shift by changing 1 °C air temperature.

We calculated the CP for both whole-body thermal sensation **-0.75 ± 0.54** K and upper-back thermal sensation - **2.85 ± 1.85** K. While the wearable cooling device in this study was relatively effective at the upper back, it had limited power for the whole body. Comparing with other PCS in the literature in Table 4, we found that fans and office chairs had an higher CP by cooling a larger body area. Table 4 only describes the PCS studies that assessed CP and does not include all local cooling solutions. The values and conditions were extracted from Zhang et al. [10] in non-neutral ambient environment. In particular, fans have shown to be the most effective in term of CP among all other systems given a maximum value of – 7 K. Office chairs have also shown a high CP level up to –5 K. Comparing the other solutions with the on this study, the proposed local cooing at the upper back had an a minimum corrective power, less than -1 K, despite the advantages in energy usage, flexibility, and potential scalability in the future application.

Table 4. Corrective Power of different PCS solutions on whole-body thermal sensation

PCS	Conditions	CP

Frontal Air Jets (Located in front of participants targeting their face)	Temperature: *26 and 27 °C* Relative Humidity: *60-80 %* Air speed: *0.36 and 0.6 m/s*	−1 K to −3 K
	Temperature: *28 °C* Relative Humidity: 7*0-80 %* Air speed: *0.4-0.6 m/s*	-2 K to -3 K
	Temperature: *30 °C* Relative Humidity: *40-80 %* Air speed: *0.8-1 m/s*	-2 K to -4 K
Fans (Located in front of participants targeting their face or above)	Temperature: *26 and 27 °C* Relative Humidity: 4*0-55%* Air speed: *0.25-0.6 m/s*	-3 K
	Temperature: *28-30 °C* Relative Humidity: *60-80 %* Air speed: *1 m/s*	-4 K to -7 K
Office Chair (Targets the back and thighs of participants)	Temperature: *29 - 30 °C* Relative Humidity: 50 %	-2 K to -5 K
Peltier Module (Placed on inner side of wrist)	Temperature: *28 °C* Relative Humidity: *40 %*	-2.5 K
The present Study **Peltier Module** (Targeting Upper-back)	Temperature: *31.5 °C* Relative Humidity: *30%*	-0.75 K

5.2 Summary of the PCS's effectiveness on cognitive performance

Table 4 summarizes the effectiveness of various PCS solutions on cognitive performance from literature, such as using a desk fan, heating desk, and head ventilation. Due to the varying properties in conditioning different body parts at various intensities, it is difficult to compare which solutions are more effective in improving cognition. Nevertheless, Table 4 shows an improvement range of approximate 5% - 30%. For instance, applying a desk fan could improve addition and multiplication task performance by 10.4% and 8.2% respectively. Also, when cooling people at multiple body parts (e.g., breathing zone, chest and back), participants performed 18% to 33% improvement in memory tasks. The current study showed a 15.38% increase in Risk Decision Taking. These findings imply an effective and probably energy-efficient approach using PCS to improve work and learning performance.

Table 4: The effect of PCS on cognition

References	PCS solution	Cognition
[30]	Breathing zone cooling Chest and back cooling Combined cooling	Calculation: + 21% to + 33% Reasoning: + 12% to + 31% Memory Task: + 18% to +33% Response Inhibition: +10% to +18%
[42]	Radiant cooling desk Desk fan Radiant cooling desk + desk fan	Fatigue: - 5% to -10%
[48]	Desk fan	Addition: +10.4 % Multiplication: +8.2%
[49]	Ventilation cooling seat Water cooling seat	Concentration index: +4.2% and +32.2 %
[50]	Desk Fans Heating desk Heating mat	Increased effort, motivation (complex task) Increase alertness (simple task)
[51]	Head cooling	Increase in spatial span (complex task): 10 %
[52]	Head ventilation device	Logical thinking: +8.5%
Current Study	Upper-back cooling	Risk Decision Taking: +15.38%

5.3 Cooling effect for different sexes

We repeated statistical analysis displayed in the Results section for male and female participants separately to determine whether local cooling is more effective for a certain sex. For females, there were 11 participants in the control group and 14 in the local cooling group. The number of male participants in the control and local cooling group was 19 and 16 respectively. In this section, we only focus on the parameters that the local cooling device exhibit a higher effect for a certain sex. However, all the results including trivial differences can be found in Appendix A7.

5.3.1 Emotion

Female participants showed statistical difference in attentive emotion (p =0.03) as well as active emotion, (p = 0.04) while male participant showed no different in all positive emotion modules. Furthermore, females' participants showed a decrease in negative emotions such as afraid (p = 0.02), nervous (p = 0.046), upset (p = 0.03), hostile ($p < 0.001$), and the overall negative emotion score (p = 0.02), while male score a decrease in negative emotions such as upset (p = 0.004), ashamed (0.044), and the overall negative emotions (p = 0.0018).

Comparing the overall analysis of the PANAS-SF data and the looking at the gender effect, we see that the female participants were the one with the significant increase in most of the positive emotion modules and adding the active emotion, which was not observed in the overall analysis, while the male participants data did not show any statistical difference. Also, looking at the negative emotions, we see that the female participants showed significant decrease in most of the negative emotions first observed in the overall analysis compared to the male participants. On the other hand, we see that the male participants showed a significant difference in the positive active emotion which was not observed for all participants data as well as the females' participants data. The analysis results of the PANAS-SF assessment for the male and female participants for the two experimental group can be found in the Appendix.

Table 5. PANAS-SF Statistical Analysis Results based on gender effect

Emotional State		P-value		
		Overall Group	**Male Group**	**Female Group**
Positive Emotions	Determined	0.34	0.47†	0.20
	Attentive	0.045 *	0.13†	0.03† *
	Alert	0.09	0.15†	0.07
	Inspired	0.26	0.18†	0.49
	Active	0.28	0.20†	0.04†*
	Overall Positive Emotion	0.23	0.16†	0.51
Negative Emotions	Afraid	0.006 **	0.05†	0.02† *
	Nervous	0.061	0.29†	0.046† *
	Upset	0.0004 ***	0.004† **	0.03† *
	Ashamed	0.27	0.044† *	0.13†
	Hostile	0.001 **	0.127	0.0005† ***
	Overall Negative Emotion	0.0018 **	0.021† *	0.02† *

† : *Mann-Whitney non-parametric results, while rest refers to the T-test parametric results*

5.4 The initial thermal sensation effect

In this section we investigate the initial thermal sensation vote effect on participants' thermal experience. The group were divided based on their initial whole-body thermal sensation vote. First, the median whole-body thermal sensation was calculated for the control group and the local cooling group. Then, the groups were divided based on their respective median values. For the control group, given that the split of the two groups was not equally distributed, whole-body preference was also considered where the median was calculated and considered as well. For the control group, 16 participants felt cooler at the initial stage of the experiment were considered as the "cool group" while 14 participants felt warmer were assigned as the "warm group." For the local cooling group 14 participants felt cooler at the initial stage were in the "cool group," while 16 participants felt warmer were in the "warm group."

5.4.1 Skin temperature

Upper-back Skin Temperature

For the upper back temperature, the warm group showed the most significant and long period drop, lasting for a 20 min period after the local cooling was applied, showing significant drop at the 5 min period ($p = 0.008$), the 10 min period ($p = 0.0002$), the 15 min period ($p = 0.0004$), and the 20 min period ($p = 0.03$). The cool group only showed a major significance at the 10 min period ($p = 0.04$), while the rest of the periods didn't show any major difference between the two groups compared to the warm group. The plot results of the upper-back skin temperature for the cool and warm groups for the two experimental groups can be found in the Appendix.

5.4.2 Emotion

The cool group showed a major statistical significance for the attentive positive emotion ($p = 0.001$), it also showed significance for the alert emotion ($p = 0.02$), and the overall positive emotion ($p= 0.02$). However, results didn't show any significance for the negative emotions for the cool group. On the other hand, the warm group showed statistical difference in the positive emotion's subscales, only for the active emotion ($p= 0.02$). Furthermore, results showed significant difference between the two experimental group for three of the negative emotions, where data showed a significance for the afraid emotion ($p = 0.002$), and the nervous emotion ($p = 0.003$), and a major significant difference for the upset emotion ($p = 0.0002$).

Comparing the two groups to the overall group data, we see that the cool group showed increase in more positive emotions than the overall group, while it didn't show any change in the negative emotions, The warm group may have showed small changes in the positive emotions, but it did show major decrease in the negative emotions compared to the overall analysis as well as the cooler group. This can suggest that the effect of local cooling showed more effect on the warm group, whereas, for the cool group, the local cooling showed some positive effect on them as well, but it was not enough to decrease any negative emotions the group had. The analysis results of the PANAS-SF assessment for the cool and warm groups for the two experimental group can be found in the Appendix.

Table 6: PANAS-SF results for the cool and warm group

Emotional State		P-value		
		Overall Group	**Cool Group**	**Warm Group**
Positive Emotions	Determined	0.34	0.07†	0.30
	Attentive	0.045 *	0.001† **	0.49
	Alert	0.09	0.02†*	0.49†

	Inspired	0.26	0.07†	0.48†
	Active	0.28	0.06†	0.02†*
	Overall Positive Emotion	0.23	0.02*	0.30†
Negative Emotions	Afraid	0.006 **	0.33†	0.002†**
	Nervous	0061	0.27†	0.003†**
	Upset	0.0004 ***	0.05†	0.0002†***
	Ashamed	0.27	0.41†	0.19†
	Hostile	0.001 **	0.17†	2.41*e*-05†***
	Overall Negative Emotion	0.0018 **	0.35†	8.26*e*-06†***

†:Mann-Whitney non-parametric results, while rest refers to the T-test parametric results

6. Limitations

The results found in this study cannot be generalized to all PCS. The application introduced in this paper is only limited to the upper back region and is also not used for extended time period. Furthermore, the effects of the local cooling strategy was applied in a scenario of occupant in an office space. The performance of this solution should be further investigated in other scenarios, different body regions and for longer time periods to further extend and understand the capabilities of the PCS solution for thermal comfort. Furthermore, it is important to note that the study focused on healthy college students and may not be generalized to all populations. Therefore, including a broader range of population should be included to establish the generalizability of the findings. Another limitation to this study is the sample size. Although the study sample size was larger than that of many comparable investigations, it is important to recognize that a larger sample size can enhance the statistical reliability of the study and obtain more robust findings.

In conclusion, while the present study contributes valuable insights into the local cooling strategy for thermal comfort, it is imperative to recognize its limitations. By addressing the limitations through further research, the field can advance toward a more comprehensive understanding of the applicability and effectiveness of the PCS solution in different contexts.

7. Conclusion

This study investigated the effect of low-energy cooling strategy in warm environment on thermal experience, emotional state, and cognitive performance. Analysis shows the following main implications as follows:

1. Individuals with local cooling can feel cooler in a warm environment and have their emotional state improved even when the effect is not that substantial.

2. Individuals with local cooling are inclined to take more risky decisions even in an uncomfortable environment.
3. Local cooling strategy can provide a CP of 2.85 ± 1.85 °C on the local scale and 0.75 ± 0.54°C for the whole-body scale.
4. Female participants displayed a greater improvement than males in their emotional state when using the wearable cooling, as evidenced by an increase in positive emotional scale and a decrease in negative emotional scale. By contrast, male participants who underwent local cooling experienced a decrease in negative emotions, while their positive emotions remained unaffected. Notably, male participants who received local cooling also exhibited a higher inclination towards taking risky decisions when compared to the male counterparts in the control group. However, such difference was not observed in female participants.
5. The warm group, comprising participants with high initial thermal sensation, demonstrated improvements in both positive and negative emotional scales when local cooling was applied. However, the wearable cooling did not improve negative emotion for the cool group, consisting of participants who underwent local cooling and initially reported less warm thermal sensation.

These findings show that the local cooling strategy can have a positive impact on the thermal experience of individuals in a warm environment (e.g., during heatwaves), improving the emotional state of individual by increasing positive emotions and decreasing negative emotions, and making the individuals more relaxed taking risky decisions towards good reward outcome with care.

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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. The role of EmberWave was limited to providing a submodule for our PCS, and had no involvement in the study design, data interpretation, manuscript preparation, or decision to publish. The findings and conclusions presented in this paper are solely based on the analysis conducted by the authors and do not reflect any undue influence from EmberWave or any other external entity.

References

[1] Department of Energy United States of America, "An Assessment of Energy Technologies and Research Opportunities," *Chapter 5: Increasing Efficiency of Building Systems and Technologies*, no. September, 2015.

[2] R. and A.-C. Engineers. American Society of Heating, *ANSI/ASHRAE Standard 55-2017 : Thermal Environmental Conditions for Human Occupancy,*. 2017.

[3] L. Pérez-Lombard, J. Ortiz, and C. Pout, "A review on buildings energy consumption information," *Energy Build*, vol. 40, no. 3, 2008, doi: 10.1016/j.enbuild.2007.03.007.

[4] M. A. Ortiz, S. R. Kurvers, and P. M. Bluyssen, "A review of comfort, health, and energy use: Understanding daily energy use and wellbeing for the development of a new approach

to study comfort," *Energy and Buildings*, vol. 152. 2017. doi: 10.1016/j.enbuild.2017.07.060.

[5] L. Lan, P. Wargocki, and Z. Lian, "Quantitative measurement of productivity loss due to thermal discomfort," in *Energy and Buildings*, 2011. doi: 10.1016/j.enbuild.2010.09.001.

[6] L. Lan, Z. Lian, L. Pan, and Q. Ye, "Neurobehavioral approach for evaluation of office workers' productivity: The effects of room temperature," *Build Environ*, vol. 44, no. 8, 2009, doi: 10.1016/j.buildenv.2008.10.004.

[7] H. Wang and L. Liu, "Experimental investigation about effect of emotion state on people's thermal comfort," *Energy Build*, vol. 211, p. 109789, Mar. 2020, doi: 10.1016/j.enbuild.2020.109789.

[8] C. Huizenga, S. Abbaszadeh, L. Zagreus, and E. Arens, "Air quality and thermal comfort in office buildings: Results of a large indoor environmental quality survey," in *HB 2006 - Healthy Buildings: Creating a Healthy Indoor Environment for People, Proceedings*, 2006.

[9] L. T. Graham, T. Parkinson, and S. Schiavon, "Lessons learned from 20 years of CBE's occupant surveys," *Buildings and Cities*, vol. 2, no. 1, 2021, doi: 10.5334/bc.76.

[10] H. Zhang, E. Arens, and Y. Zhai, "A review of the corrective power of personal comfort systems in non-neutral ambient environments," *Build Environ*, vol. 91, 2015, doi: 10.1016/j.buildenv.2015.03.013.

[11] R. J. de Dear and G. S. Brager, "Developing an adaptive model of thermal comfort and preference," in *ASHRAE Transactions*, 1998.

[12] Y. Al horr, M. Arif, M. Katafygiotou, A. Mazroei, A. Kaushik, and E. Elsarrag, "Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature," *International Journal of Sustainable Built Environment*, vol. 5, no. 1. 2016. doi: 10.1016/j.ijsbe.2016.03.006.

[13] V. De Giuli, O. Da Pos, and M. De Carli, "Indoor environmental quality and pupil perception in Italian primary schools," *Build Environ*, vol. 56, 2012, doi: 10.1016/j.buildenv.2012.03.024.

[14] L. Lan and Z. Lian, "Use of neurobehavioral tests to evaluate the effects of indoor environment quality on productivity," *Build Environ*, vol. 44, no. 11, 2009, doi: 10.1016/j.buildenv.2009.02.001.

[15] R. Rawal, M. Schweiker, O. B. Kazanci, V. Vardhan, Q. Jin, and L. Duanmu, "Personal comfort systems: A review on comfort, energy, and economics," *Energy and Buildings*, vol. 214. 2020. doi: 10.1016/j.enbuild.2020.109858.

[16] T. Parkinson, R. De Dear, and C. Candido, "Thermal pleasure in built environments: Alliesthesia in different thermoregulatory zones," *Building Research and Information*, vol. 44, no. 1, 2016, doi: 10.1080/09613218.2015.1059653.

[17] J. Kim *et al.*, "Occupant comfort and behavior: High-resolution data from a 6-month field study of personal comfort systems with 37 real office workers," *Build Environ*, vol. 148, pp. 348–360, Jan. 2019, doi: 10.1016/j.buildenv.2018.11.012.

[18] T. Hoyt, E. Arens, and H. Zhang, "Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings," *Build Environ*, vol. 88, 2015, doi: 10.1016/j.buildenv.2014.09.010.

[19] M. Veselý and W. Zeiler, "Personalized conditioning and its impact on thermal comfort and energy performance - A review," *Renewable and Sustainable Energy Reviews*, vol. 34. 2014. doi: 10.1016/j.rser.2014.03.024.

[20] H. Wang, M. Xu, and C. Bian, "Experimental comparison of local direct heating to improve thermal comfort of workers," *Build Environ*, vol. 177, p. 106884, Jun. 2020, doi: 10.1016/j.buildenv.2020.106884.

[21] S. Y. Xia Y, "Relationship between anxiety and monotonous task performance in response to local cooling: an experimental study in healthy young men," *Ergonomics*, pp. 1–11, Jun. 2022.

[22] W. Pasut, H. Zhang, E. Arens, and Y. Zhai, "Energy-efficient comfort with a heated/cooled chair: Results from human subject tests," *Build Environ*, vol. 84, 2015, doi: 10.1016/j.buildenv.2014.10.026.

[23] W. Pasut, H. Zhang, E. Arens, S. Kaam, and Y. Zhai, "Effect of a heated and cooled office chair on thermal comfort," in *HVAC and R Research*, 2013. doi: 10.1080/10789669.2013.781371.

[24] Y. He, X. Wang, N. Li, M. He, and D. He, "Heating chair assisted by leg-warmer: A potential way to achieve better thermal comfort and greater energy conservation in winter," *Energy Build*, vol. 158, 2018, doi: 10.1016/j.enbuild.2017.11.006.

[25] Y. He, N. Li, N. Li, J. Li, J. Yan, and C. Tan, "Control behaviors and thermal comfort in a shared room with desk fans and adjustable thermostat," *Build Environ*, vol. 136, 2018, doi: 10.1016/j.buildenv.2018.03.049.

[26] H. Maula, V. Hongisto, H. Koskela, and A. Haapakangas, "The effect of cooling jet on work performance and comfort in warm office environment," *Build Environ*, vol. 104, 2016, doi: 10.1016/j.buildenv.2016.04.018.

[27] W. Cui, G. Cao, Q. Ouyang, and Y. Zhu, "Influence of dynamic environment with different airflows on human performance," *Build Environ*, vol. 62, 2013, doi: 10.1016/j.buildenv.2013.01.008.

[28] C. Habchi, K. Ghali, N. Ghaddar, W. Chakroun, and S. Alotaibi, "Ceiling personalized ventilation combined with desk fans for reduced direct and indirect cross-contamination and efficient use of office space," *Energy Convers Manag*, vol. 111, 2016, doi: 10.1016/j.enconman.2015.12.067.

[29] H. Yang, B. Cao, Y. Ju, and Y. Zhu, "The effects of local cooling at different torso parts in improving body thermal comfort in hot indoor environments," *Energy Build*, vol. 198, pp. 528–541, Sep. 2019, doi: 10.1016/j.enbuild.2019.06.004.

[30] J. Tang, Y. Liu, H. Du, L. Lan, Y. Sun, and J. Wu, "The effects of portable cooling systems on thermal comfort and work performance in a hot environment," *Build Simul*, vol. 14, no. 6, pp. 1667–1683, Dec. 2021, doi: 10.1007/s12273-021-0766-y.

[31] H. Oi, K. Yanagi, K. Tabat, and Y. Tochihar, “Effects of heated seat and foot heater on thermal comfort and heater energy consumption in vehicle,” *Ergonomics*, vol. 54, no. 8, 2011, doi: 10.1080/00140139.2011.595513.

[32] H. Zhang *et al.*, “Using footwarmers in offices for thermal comfort and energy savings,” *Energy Build*, vol. 104, 2015, doi: 10.1016/j.enbuild.2015.06.086.

[33] H. Wang, J. Wang, W. Li, and S. Liang, “Experimental study on a radiant leg warmer to improve thermal comfort of office workers in winter,” *Build Environ*, vol. 207, 2022, doi: 10.1016/j.buildenv.2021.108461.

[34] F. S. Bauman, T. G. Carter, A. V. Baughman, and E. A. Arens, “Field study of the impact of a desktop task/ambient conditioning system in office buildings,” in *ASHRAE Transactions*, 1998.

[35] T. Y. Chang and A. Kajackaite, “Battle for the thermostat: Gender and the effect of temperature on cognitive performance,” *PLoS One*, vol. 14, no. 5, 2019, doi: 10.1371/journal.pone.0216362.

[36] Z. Wang *et al.*, “Evaluating the comfort of thermally dynamic wearable devices,” *Build Environ*, vol. 167, 2020, doi: 10.1016/j.buildenv.2019.106443.

[37] B. Yang, T. H. Lei, P. Yang, K. Liu, and F. Wang, “On the use of wearable face and neck cooling fans to improve occupant thermal comfort in warm indoor environments,” *Energies (Basel)*, vol. 14, no. 23, 2021, doi: 10.3390/en14238077.

[38] M. Luo, E. Arens, H. Zhang, A. Ghahramani, and Z. Wang, “Thermal comfort evaluated for combinations of energy-efficient personal heating and cooling devices,” *Build Environ*, vol. 143, 2018, doi: 10.1016/j.buildenv.2018.07.008.

[39] W. Song, Z. Zhang, Z. Chen, F. Wang, and B. Yang, “Thermal comfort and energy performance of personal comfort systems (PCS): A systematic review and meta-analysis,” *Energy and Buildings*, vol. 256. 2022. doi: 10.1016/j.enbuild.2021.111747.

[40] J. Kaczmarczyk and J. Ferdyn-Grygierek, “Thermal comfort and energy use with local heaters,” *Energies (Basel)*, vol. 13, no. 11, 2020, doi: 10.3390/en13112912.

[41] S. Watanabe, A. K. Melikov, and G. L. Knudsen, “Design of an individually controlled system for an optimal thermal microenvironment,” *Build Environ*, vol. 45, no. 3, 2010, doi: 10.1016/j.buildenv.2009.07.009.

[42] Y. He, N. Li, X. Wang, M. He, and D. He, “Comfort, energy efficiency and adoption of personal cooling systems in warm environments: A field experimental study,” *Int J Environ Res Public Health*, vol. 14, no. 11, 2017, doi: 10.3390/ijerph14111408.

[43] W. Luo, R. Kramer, Y. de Kort, and W. van Marken Lichtenbelt, “Effectiveness of personal comfort systems on whole-body thermal comfort – A systematic review on which body segments to target,” *Energy Build*, vol. 256, 2022, doi: 10.1016/j.enbuild.2021.111766.

[44] T. Parkinson and R. De Dear, “Thermal pleasure in built environments: Physiology of alliesthesia,” *Building Research and Information*, vol. 43, no. 3, 2015, doi: 10.1080/09613218.2015.989662.

[45] Y. He *et al.*, “Creating alliesthesia in cool environments using personal comfort systems,” *Build Environ*, vol. 209, 2022, doi: 10.1016/j.buildenv.2021.108642.

[46] Y. Geng, W. Ji, B. Lin, and Y. Zhu, “The impact of thermal environment on occupant IEQ perception and productivity,” *Build Environ*, vol. 121, 2017, doi: 10.1016/j.buildenv.2017.05.022.

[47] P. Roelofsen, “The impact of office environments on employee performance: The design of the workplace as a strategy for productivity enhancement,” *Journal of Facilities Management*, vol. 1, no. 3. 2002. doi: 10.1108/14725960310807944.

[48] A. C. Boerstra, M. te Kulve, J. Toftum, M. G. L. C. Loomans, B. W. Olesen, and J. L. M. Hensen, “Comfort and performance impact of personal control over thermal environment in summer: Results from a laboratory study,” *Build Environ*, vol. 87, 2015, doi: 10.1016/j.buildenv.2014.12.022.

[49] Y. Shin, M. Lee, and H. Cho, “Analysis of EEG, cardiac activity status, and thermal comfort according to the type of cooling seat during rest in indoor temperature,” *Applied Sciences (Switzerland)*, vol. 11, no. 1, 2021, doi: 10.3390/app11010097.

[50] W. Luo, R. Kramer, Y. de Kort, P. Rense, J. Adam, and W. van Marken Lichtenbelt, “Personal comfort systems and cognitive performance: Effects on subjective measures, cognitive performance, and heart rate measures,” *Energy Build*, vol. 278, p. 112617, 2023, doi: https://doi.org/10.1016/j.enbuild.2022.112617.

[51] N. Gaoua, S. Racinais, J. Grantham, and F. El Massioui, “Alterations in cognitive performance during passive hyperthermia are task dependent,” *International Journal of Hyperthermia*, vol. 27, no. 1, 2011, doi: 10.3109/02656736.2010.516305.

[52] H. Zhang, E. Arens, D. E. Kim, E. Buchberger, F. Bauman, and C. Huizenga, “Comfort, perceived air quality, and work performance in a low-power task-ambient conditioning system,” *Build Environ*, vol. 45, no. 1, 2010, doi: 10.1016/j.buildenv.2009.02.016.

[53] “Embr Labs Inc.”

[54] M. J. Smith *et al.*, “Augmenting smart buildings and autonomous vehicles with wearable thermal technology,” in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 2017. doi: 10.1007/978-3-319-58077-7_44.

[55] H. Yang, B. Cao, Y. Ju, and Y. Zhu, “The effects of local cooling at different torso parts in improving body thermal comfort in hot indoor environments,” *Energy Build*, vol. 198, 2019, doi: 10.1016/j.enbuild.2019.06.004.

[56] M. Jahadi and H. Dehghan, “Design and Validation of Novel Evaporative Local Cooling Coatings to Prevent Adverse Health Effects of Heat Exposure.,” *Int J Prev Med*, vol. 14, p. 30, 2023, doi: 10.4103/ijpvm.ijpvm_342_21.

[57] J. A. J. Stolwijk and J. D. Hardy, "Temperature regulation in man ? A theoretical study," *Pflügers Archiv für die Gesamte Physiologie des Menschen und der Tiere (1966)*, vol. 291, no. 2, pp. 129–162, 1966, doi: 10.1007/BF00412787.

[58] M. Mokhtari Yazdi and M. Sheikhzadeh, "Personal cooling garments: a review," *The Journal of The Textile Institute*, vol. 105, no. 12, pp. 1231–1250, Dec. 2014, doi: 10.1080/00405000.2014.895088.

[59] E. Shvartz, "Effect of neck versus chest cooling on responses to work in heat," *J Appl Physiol*, vol. 40, no. 5, pp. 668–672, May 1976, doi: 10.1152/jappl.1976.40.5.668.

[60] E. R. Thompson, "Development and Validation of an Internationally Reliable Short-Form of the Positive and Negative Affect Schedule (PANAS)," *J Cross Cult Psychol*, vol. 38, no. 2, pp. 227–242, Mar. 2007, doi: 10.1177/0022022106297301.

[61] A. Mackinnon, A. F. Jorm, H. Christensen, A. E. Korten, P. A. Jacomb, and B. Rodgers, "A short form of the Positive and Negative Affect Schedule: Evaluation of factorial validity and invariance across demographic variables in a community sample," *Pers Individ Dif*, vol. 27, no. 3, 1999, doi: 10.1016/S0191-8869(98)00251-7.

[62] S. G. Hart and L. E. Staveland, "Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research," 1988, pp. 139–183. doi: 10.1016/S0166-4115(08)62386-9.

[63] E. DE RENZI and L. A. VIGNOLO, "THE TOKEN TEST: A SENSITIVE TEST TO DETECT RECEPTIVE DISTURBANCES IN APHASICS," *Brain*, vol. 85, no. 4, pp. 665–678, 1962, doi: 10.1093/brain/85.4.665.

[64] A. R. Jensen and W. D. Rohwer, "The stroop color-word test: A review," *Acta Psychol (Amst)*, vol. 25, no. C, 1966, doi: 10.1016/0001-6918(66)90004-7.

[65] C. and R. D. and S. C. and T. D. and W. K. Englund, "Unified Tri-Service Cognitive Performance Assessment Battery (UTC-PAB). 1. Design and Specification of the Battery," Feb. 1987.

[66] C. W. Lejuez, W. M. Aklin, M. J. Zvolensky, and C. M. Pedulla, "Evaluation of the Balloon Analogue Risk Task (BART) as a predictor of adolescent real-world risk-taking behaviours," *J Adolesc*, vol. 26, no. 4, 2003, doi: 10.1016/S0140-1971(03)00036-8.

[67] H. E. Rosvold, A. F. Mirsky, I. Sarason, E. D. Bransome, and L. H. Beck, "A continuous performance test of brain damage," *J Consult Psychol*, vol. 20, no. 5, 1956, doi: 10.1037/h0043220.

[68] J. P. GUILFORD, "Creativity: Yesterday, Today and Tomorrow," *J Creat Behav*, vol. 1, no. 1, 1967, doi: 10.1002/j.2162-6057.1967.tb00002.x.

[69] C. Wang *et al.*, "How indoor environmental quality affects occupants' cognitive functions: A systematic review," *Building and Environment*, vol. 193. 2021. doi: 10.1016/j.buildenv.2021.107647.

[70] W. Liu, Z. Lian, Q. Deng, and Y. Liu, "Evaluation of calculation methods of mean skin temperature for use in thermal comfort study," *Build Environ*, vol. 46, no. 2, 2011, doi: 10.1016/j.buildenv.2010.08.011.

[71] R. De Dear, "Revisiting an old hypothesis of human thermal perception: Alliesthesia," *Building Research and Information*, vol. 39, no. 2, 2011, doi: 10.1080/09613218.2011.552269.

[72] P. Virtanen *et al.*, "SciPy 1.0: fundamental algorithms for scientific computing in Python," *Nat Methods*, vol. 17, no. 3, pp. 261–272, Mar. 2020, doi: 10.1038/s41592-019-0686-2.

[73] J. Cohen, *Statistical Power Analysis for the Behavioral Sciences*. Routledge, 2013. doi: 10.4324/9780203771587.

[74] C. J. Lau, M. Loebel Roson, K. M. Klimchuk, T. Gautam, B. Zhao, and R. Zhao, "Particulate matter emitted from ultrasonic humidifiers—Chemical composition and implication to indoor air," *Indoor Air*, vol. 31, no. 3, 2021, doi: 10.1111/ina.12765.

Appendix:

A1. Environmental chamber

Figure A.1. shows the different environmental parameters for all participants in both groups. It should be noted that the high level of the indoor particle matter PM2.5 is due to the ultrasonic humidifier used in the experiment to reach the desired relative humidity. The humidifier converts all the non-volatile solutes in tap water into PM, which is innocuous and not harmful to the participants as studies have shown [74].

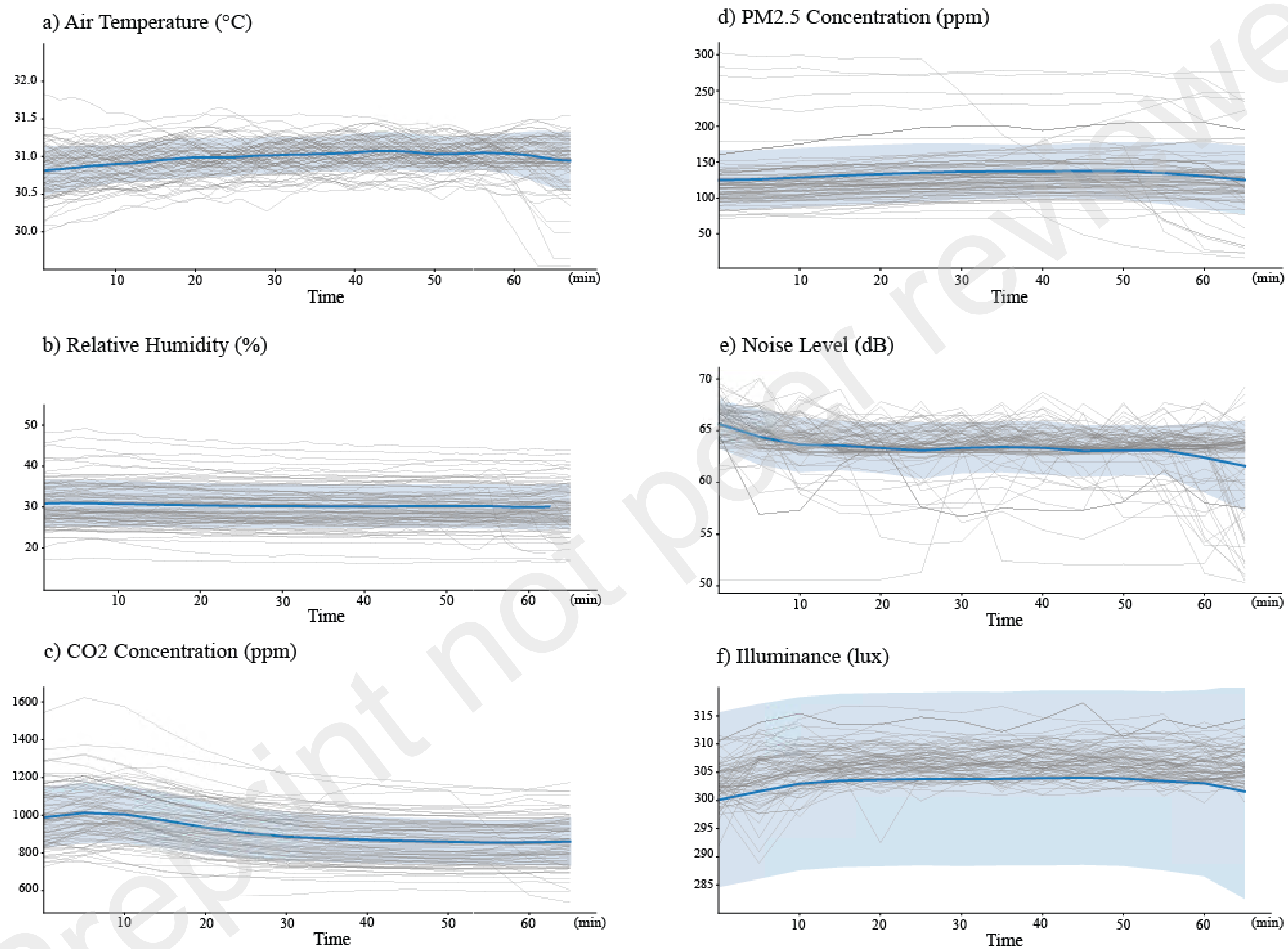


Figure A1. *Indoor environmental conditions of in the test chamber during experiments*

A2. Subjects

Table A2. General Information of the control group and local cooling group

	Control Group	Local Cooling Group	p-value (Mann Whitney U†)
Participants	Female 11	Female 14	-
	Male 19	Male 16	
Age Mean ± std	20.39 ± 4.66	21.10 ± 2.11	0.23
Height (cm) Mean ± std	171.33 ± 9.84	172.47 ± 9.10	0.33
Weight (kg) *Mean ± std*	70.31 ± 12.58	69.43 ± 14.49	0.34
Exercise time (hr / week) Mean ± std	7.69 ± 6.45	6.58 ± 4.46	0.47

†The Mann Whitney U test was used to compare the difference of subject characteristics between the control and experimental group (local cooling). No significant differences were observed between the two groups.

A3. Questionnaires

A3.1. Thermal evaluation

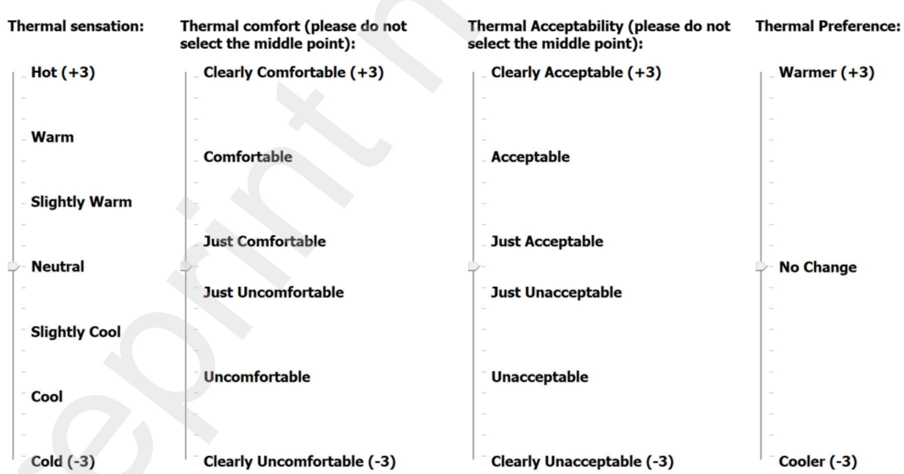
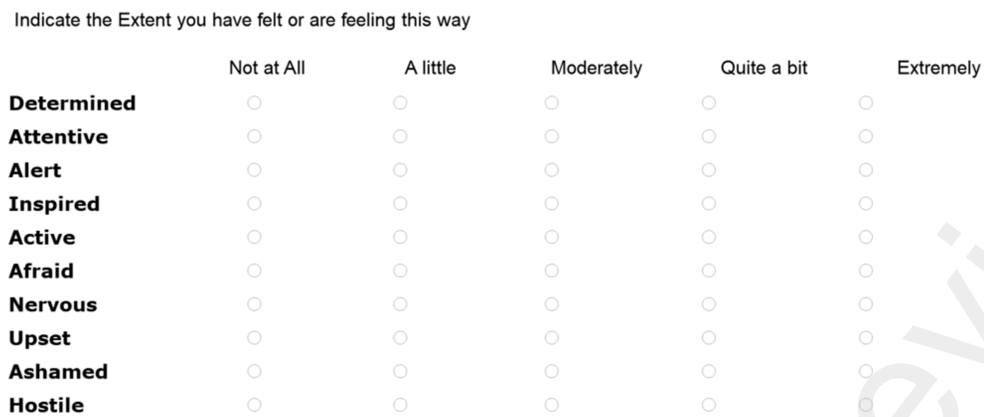


Figure A3.1 Thermal subjective questionnaire

A3.2. PANAS-SF emotion evaluation


Indicate the Extent you have felt or are feeling this way

	Not at All	A little	Moderately	Quite a bit	Extremely
Determined	○	○	○	○	○
Attentive	○	○	○	○	○
Alert	○	○	○	○	○
Inspired	○	○	○	○	○
Active	○	○	○	○	○
Afraid	○	○	○	○	○
Nervous	○	○	○	○	○
Upset	○	○	○	○	○
Ashamed	○	○	○	○	○
Hostile	○	○	○	○	○

Figure A3.2 PANAS-SF emotion questionnaire

A3.3. NASA-TLX evaluation

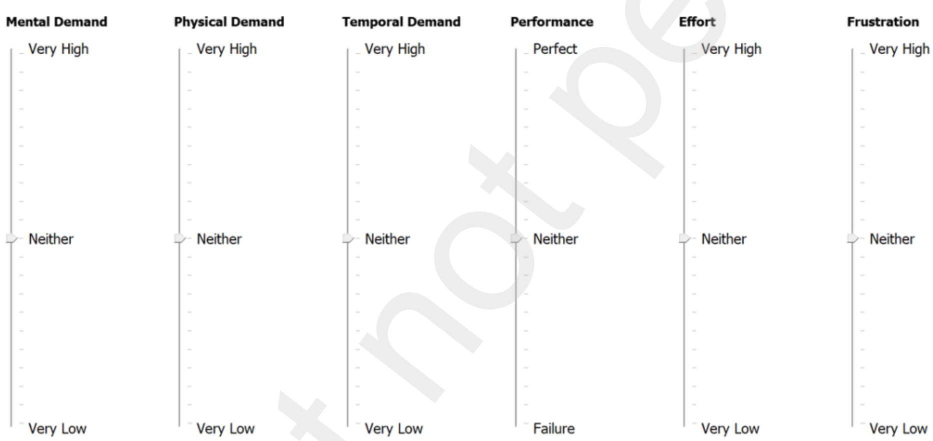
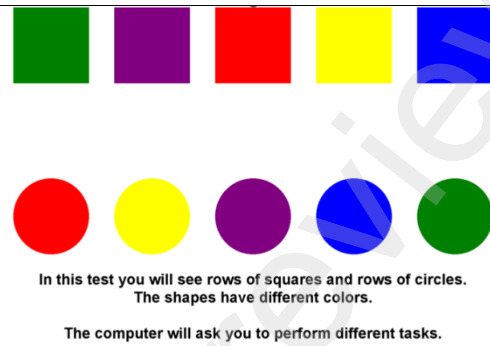


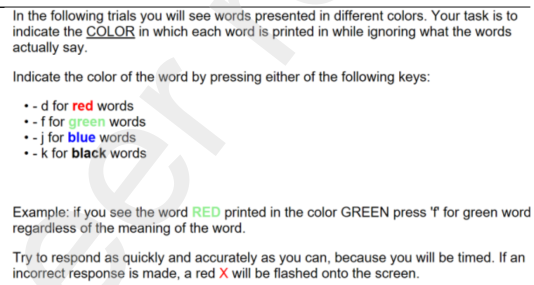
Figure A3.3. NASA-TLX questionnaire

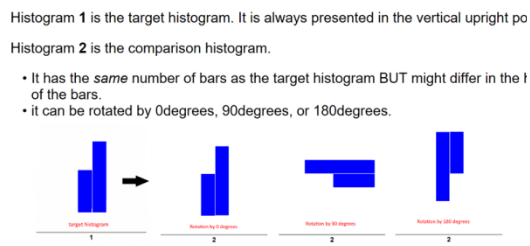
A4. Cognitive tasks

Table A4. Description on cognitive tasks

<table>
<tr><th>Cognitive task</th><th>Task interface</th></tr>
<tr><td>Token Task: Working memory

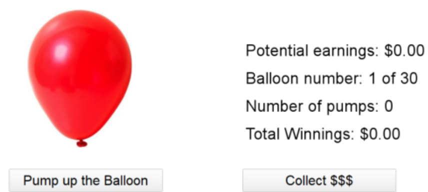
Participants are presented with a row of rectangles and circles in different colors and sizes and are given a visual and auditory instructions of what do with these shapes. The task consists of 5 phases of trials that are getting progressive. Performance was measured in terms of the number of the tokens correctly done with a range of 0-100.</td><td>
</td></tr>
<tr><td>Stroop Color Task: Response inhibition

Participants are presented with either the word "red", "green", "blue", or "black" on a white screen with a red, green, blue, or black colored font. The task consists of congruent and incongruent trials. In congruent trials, the printed word, and the color in which it was printed are matched. For incongruent trials, the printed word and the font color did not match. Performance was measured in terms of the proportion of the correct answers and the reaction time</td><td>
</td></tr>
<tr><td>Spatial Processing Task: Short-term memory

Participants are presented with a sequential template of 2,4,6 histogram bar and a spatially rotated comparison histogram. The second histogram can be rotated clockwise 0 deg, 90 deg, or 180 deg. The participants need to compare as fast as possible if the comparison histogram is congruent or incongruent to the original histogram. The number of bars and the rotation of the histogram presents the difficulty of the cognitive demand the participant needs. Performance was measured in terms of the proportion of the correct answers for 0, 90, and 180 degrees, and the reaction time.</td><td>
</td></tr>
</table>

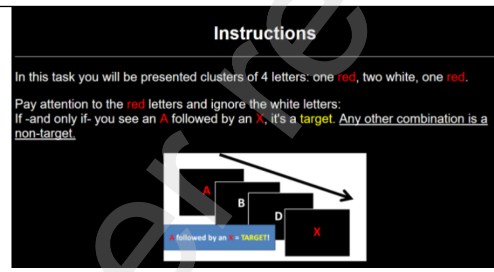
Balloon Analogue Risk Task (BART): Risk taking

Participants are given 30 balloons. For each balloon they get the choice to pump up the balloon or collect their winnings. For each successful pump, they can earn $0.01. However, if the balloon pops, which can happen on a random basis, they all the potential winning for that balloon. Performance was measured in terms of the total explosion, , the adjusted total pump count, and the average adjusted pump count.



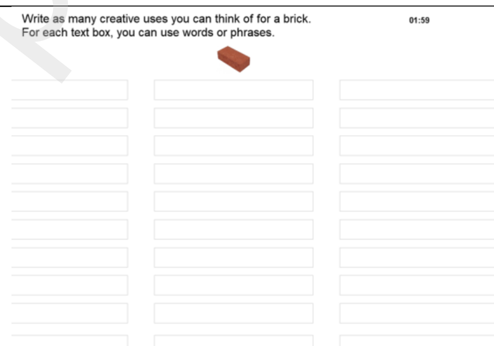
AX-Continuous Processing Task (AX-CPT): Attention

Participants are presented with a sequence of letters. The letters are presented as cue-distractor-distractor-probe and must decide if the probe is a target (cue = A, probe = X) or not. If the probe is a target, participants press the 'E'; if it's not a target they press the 'I' key. Performance was measured in terms of the proportion of the correct answers, and the reaction time.



Alternative User Task (UAT): Creativity

Participants are given 3 common objects (e.g., newspaper) and are asked to generate as many creative uses as possible for the current object within a 3-min frame. Next participants are asked to select the top 2 uses given for each object. Performance was measured in terms of the average score



A5. Skin temperature sensors

a) IButton Temperature Sensor

b) g.tec Skin Temperature Sensor (Upper-Back)

Figure A4. a) IButton skin temperature sensor (right arm, right thigh, right calf, left chest).
b) g.tec temperature sensor (upper-back)

A6. Results for All Participants

A6.1 Thermal Evaluation

Table A6.1 Statistical summary of the whole body and local thermal evaluation for the two groups

Responses to the survey		Mean ± SD: Control Group	Mean ± SD: Local Cooling Group	P-value	Cohen's d
Thermal Sensation (Whole-body)	Pre	1.26 ± 0.56	1.35 ± 0.61	0.20†	- 0.136
	Right-after	-	0.87 ± 0.86	0.02† *	0.537
	1st	1.24 ± 0.81	1.28 ± 0.67	0.41†	-0.058
	2nd	1.51 ± 0.74	0.99 ± 1.03	0.02† *	-0.586
	3rd	1.40 ± 0.89	1.37 ± 0.85	0.43†	-0.030
	All votes	1.37 ± 0.72	1.12 ± 0.90	0.03† *	0.302
Thermal Sensation (Upper Back)	Pre	0.71 ± 0.66	0.49 ± 0.79	0.195†	0.298
	Right-after	-	-0.40 ± 1.37	0.001† ***	1.020
	1st	0.89 ± 0.54	0.16 ± 1.31	0.017† *	0.721
	2nd	1.15 ± 0.73	0.11 ± 1.29	0.001 ***	0.987

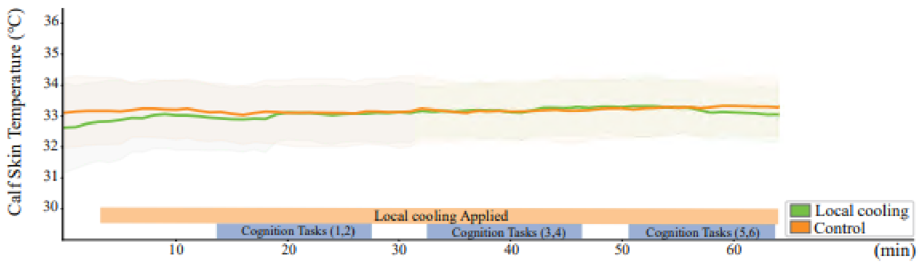
	3rd	1.17 ± 0.90	0.30 ± 1.34	0.005 ***	0.756
	All votes	0.98 ± 0.73	0.04 ± 1.34	0.001† ***	0.862
Thermal Comfort (Whole-body)	Pre	0.08 ± 0.96	0.10 ± 1.04	0.95	-0.016
	Right-after	-	0.21 ± 1.16	0.63	-0.125
	1st	-0.09 ± 1.39	-0.04 ± 1.36	0.31†	-0.035
	2nd	-0.38 ± 1.56	0.06 ± 1.50	0.22	-0.317
	3rd	-0.20 ± 1.58	-0.25 ± 1.51	0.92	0.026
	All votes	-0.14 ± 1.39	0.01 ± 1.38	0.13†	-0.114
Thermal Comfort (Upper Back)	Pre	0.64 ± 1.41	0.59 ± 1.11	0.87	0.041
	Right-after	-	0.20 ± 1.22	0.20	0.334
	1st	0.31 ± 1.31	0.05 ± 1.10	0.28†	0.209
	2nd	-0.03 ± 1.44	0.18 ± 1.33	0.50†	-0.107
	3rd	-0.10 ± 1.41	-0.03 ± 1.43	0.50†	0.050
	All votes	0.22 ± 1.41	0.10 ± 1.26	0.32†	0.088
Thermal Acceptability (Whole-body)	Pre	0.54 ± 1.21	0.68 ± 1.04	0.64	-0.122
	Right-after	-	0.57 ± 1.14	0.47†	-0.025
	1st	0.27 ± 1.28	0.32 ± 1.30	0.49†	0.036
	2nd	0.11 ± 1.45	0.56 ± 1.48	0.24	0.303
	3rd	0.13 ± 1.91	0.01 ± 1.65	0.86	0.045
	All votes	0.24 ± 1.39	0.40 ± 0.39	0.16†	-0.106
Thermal Acceptability (Upper Back)	Pre	0.85 ± 1.32	0.74 ± 0.94	0.71	0.095
	Right-after	-	0.67 ± 1.12	0.56	0.150
	1st	0.60 ± 1.29	0.61 ± 1.21	0.35†	0.011
	2nd	0.56 ± 1.47	0.47 ± 1.41	0.81	-0.063
	3rd	0.03 ± 1.61	0.33 ± 1.49	0.60	0.137
	All votes	0.53 ± 1.37	0.52 ± 1.31	0.41†	0.013
Thermal Preference (Whole-body)	Pre	-1.10 ± 1.16	-0.87 ± 1.21	0.12†	-0.196
	Right-after	-	-0.92 ± 1.09	0.09†	-0.159
	1st	-1.15 ± 1.13	-1.13 ± 1.21	0.27†	-0.025

	2nd	-1.26 ± 1.07	-1.10 ± 1.22	0.60	0.136
	3rd	-1.22 ± 1.23	-1.21 ± 1.12	0.38†	0.003
	All votes	-1.17 ± 1.15	-1.10 ± 1.13	0.06	-0.068
Thermal Preference (Upper Back)	Pre	-0.91 ± 0.86	-0.83 ± 0.90	0.31†	0.091
	Right-after	-	-0.70 ± 1.10	0.195†	-0.210
	1st	-1.02 ± 1.17	-0.95 ± 1.00	0.40†	-0.063
	2nd	-1.17 ± 1.03	-0.94 ± 1.19	0.43	0.202
	3rd	-1.10 ± 0.94	-1.07 ± 1.15	0.92†	0.027
	All votes	-0.95 ± -1.03	-0.93 ± 1.15	0.14	-0.094

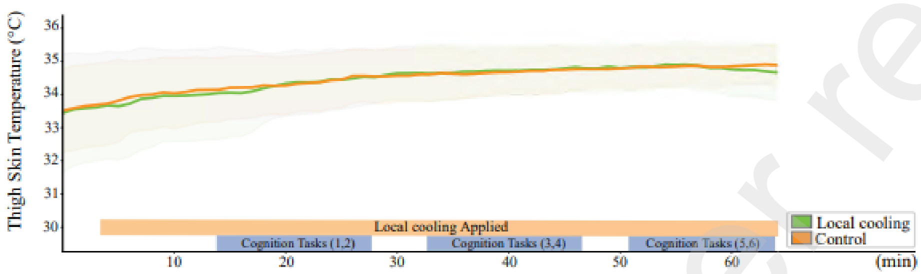
†:Mann-Whitney non-parametric results, while rest refers to the T-test parametric results

A.6.2 Skin Temperature

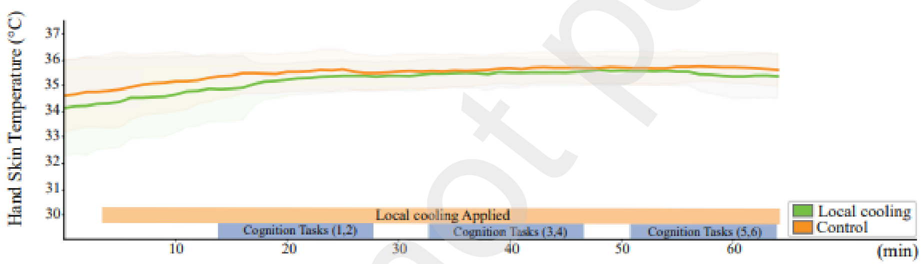
a) Calf Skin Temperature



b) Thigh Skin Temperature



c) Hand Skin Temperature



d) Chest Skin Temperature

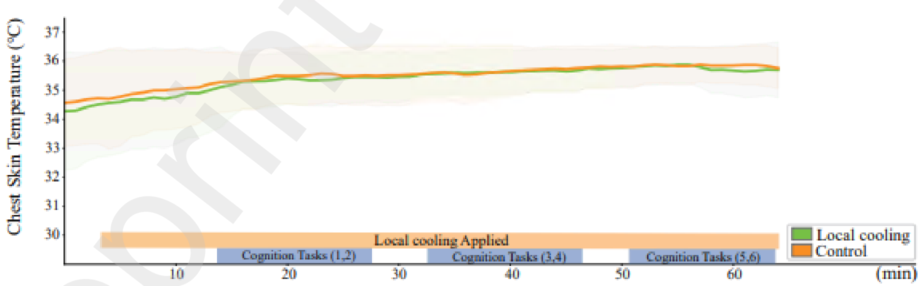


Figure A6.1 a) Skin Temperature measurements for right thigh. **b)** Skin Temperature measurements for right calf. **c)** Skin Temperature measurements for right hand. **d)** Skin Temperature measurements for left chest

A6.3 NASA-TLX Performance Questionnaire

Table A6.2 NASA-TLX statistical analysis results

Task Load	Mean ± SD		p-value	Cohen's d
	Control Group	Local Cooling Group		
Mental Demand	4.42 ± 1.48	4.51 ± 1.40	0.94†	0.065
Physical Demand	3.86 ± 3.94	1.55 ± 1.79	0.94†	0.124
Temporal Demand	4.17 ± 1.69	4.62 ± 1.28	0.39†	0.295
Performance	4.78 ± 1.55	5.11 ± 1.09	0.74†	0.270
Effort	4.20 ± 1.70	4.97 ± 1.11	0.15†	0.535
Frustration	4.02 ± 1.59	3.37 ± 1.89	0.20†	-0.375
Total Task Load	3.82 ± 0.92	4.02 ± 0.66	0.52	0.252

†:Mann-Whitney non-parametric results, while rest refers to the T-test parametric results

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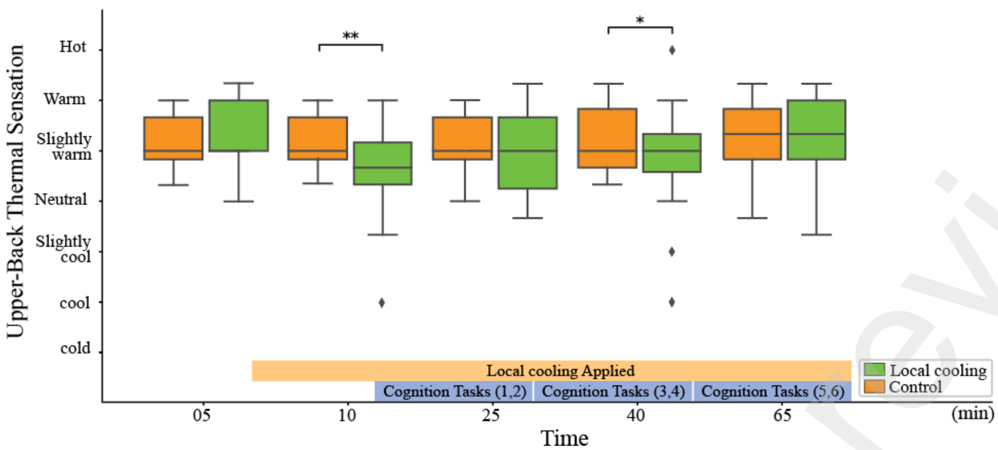
A.7 Cooling effect for different sexes

A.7.1 Thermal evaluation

Upper-back thermal sensation

Comparing the UBTS between the control group and the local cooling group. The experimental female participants showed more drop in thermal sensation between the control group (*1.01 ± 0.86*) and the experimental group (*-0.08 ± 1.45*) as compared to the male participants who showed a smaller drop between the control group (*0.91 ± 0.61)* and the experimental group (*0.15 ± 1.26*). Furthermore, as we can see from figure female participant showed longer reduction in UBTS compared to male participants. The results showed that female participants had significant reduction in thermal sensation after the local cooling was applied (p = 0.04), the first cognitive test at 25 min timeline (p = 0.04), and the second cognitive test at 40 min timeline (p = 0.01), while the last cognitive test at 60 min didn't show any significance. The male participants showed significant different right after the local cooling was applied (*p = 0.001)*, and for the second cognitive test at 40 min timeline (*p = 0.02)*.

a) Upper-Back thermal sensation for male participant



b) Upper-Back thermal sensation for female participant

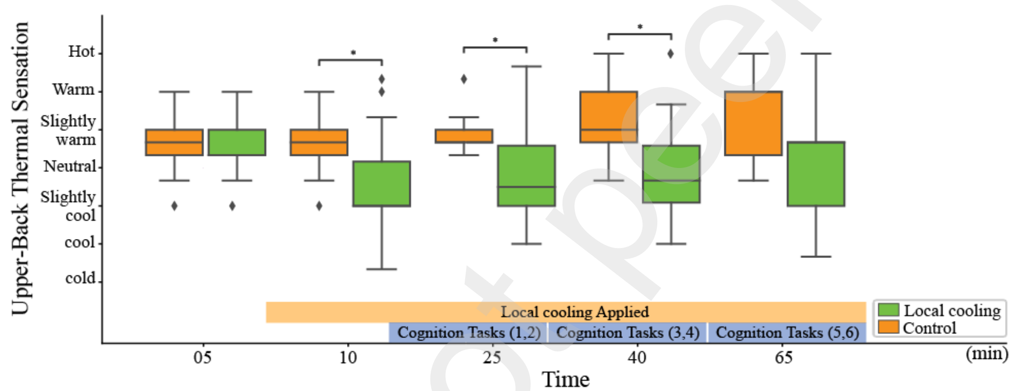


Figure A7.1 ***a) Upper-Back Thermal Sensation Boxplot for male participants***. *The second boxplot shows significant statistical difference in the thermal sensation for local cooling group (*$p = 0.001$*). The votes at cognitive tasks show a relative and significant statistical difference respectively (* $p = 0.017$ *for first test;* $p = 0.001$ *and* $p = 0.005$ *for second and third task).* ***b) Upper-Back Thermal Sensation Boxplot for female participants****. Significant difference after applying local cooling (p = 0.04), at the first test (p = 0.04),and second test (p = 0.01), no significant difference at the third cognitive task*

Whole-body thermal sensation

Male participants showed a statistical difference (*p = 0.02)* between the control (*1.20 ± 0.61*) and local cooling (*0.90 ± 0.96*) groups, while the analysis showed no difference for the female participants, suggesting that the female participants despite having a difference in the local sensation, their WBTS wasn't affected. Also, by looking at the mean values and the deviation of the votes, no significant difference was seen between the two groups.

Whole-body thermal preference:

Compared to the whole-body analysis between the control and experimental groups, gender comparison showed a difference in thermal preference for female and male participants individually. Data shows that female participants showed a statistical difference for whole-body thermal preference right after the local cooling was applied (*p*= *0.03*). Also, data showed a significant difference for the whole-body thermal preference vote (*p* = *<0.001)* between the control group *(-1.59 ± 1.07*) and the local cooling group (*-0.92 ± 1.20*) . Male participant dd not show any preference difference between the two experimental conditions. These results suggests that female participants change of temperature was preferred on a much higher scale than the male participant. . The plot results of the whole-body thermal preference for the male and female groups for the two experimental groups can be seen below.

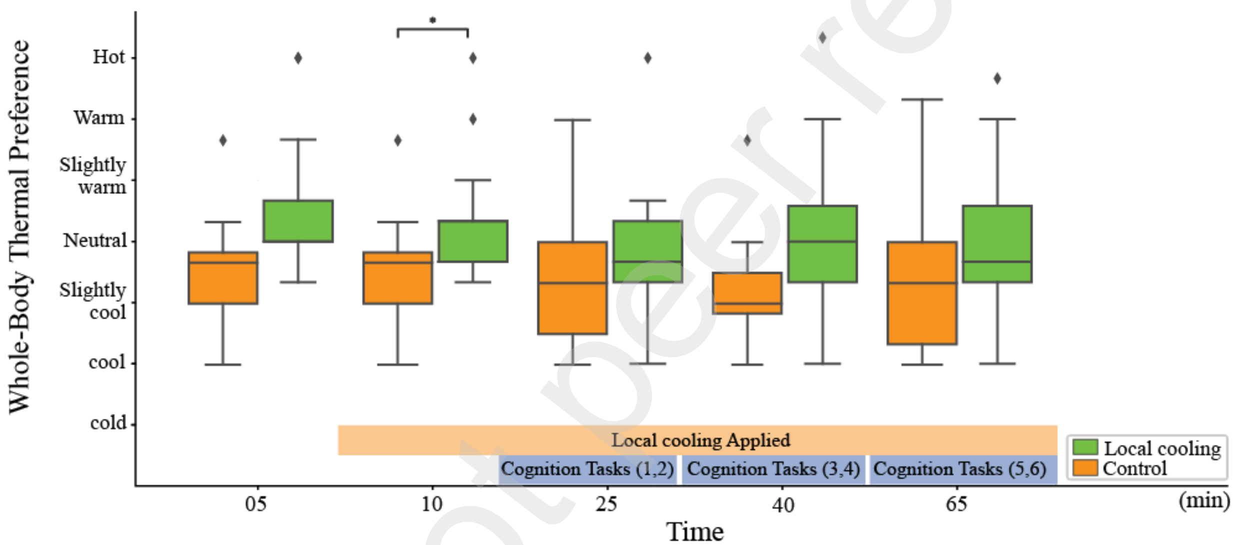


Figure A7.2 Whole-body Thermal Preference female Participant. The second boxplot shows statistical difference in the thermal preference for female in terms of local cooling group (p = 0.03)

Results of statistical tests

Table A7.1 Statistical summary of the whole body and local thermal evaluation for male participants

Responses to the survey		**Mean ± SD**		**P-value**	**Cohen's d**
		Control Group (n=30)	**Local Cooling Group (n= 30)**		
Thermal Sensation (Whole-body)	Pre	1.21 ± 0.57	1.27 ± 0.75	0.32†	0.091
	Right-after	1.21 ± 0.57	0.64 ± 1.01	**0.04**	-0.70
	1st	1.12 ± 0.59	0.98 ± 0.82	0.55	-0.20
	2nd	1.26 ± 0.64	0.78 ± 1.10	0.13	-0.52

	3rd	1.21 ± 0.73	1.12 ± 0.87	0.93	-0.029
	All votes	1.20 ± 0.61	0.90 ± 0.96	**0.02**†	-0.29
Thermal Sensation (Upper-Back)	Pre	0.82 ± 0.56	0.46 ± 0.86	0.13	-0.51
	Right-after	0.82 ± 0.56	- 0.35 ± 1.34	**0.001**	-1.19
	1st	0.86 ± 0.56	0.35 ± 1.24	0.12	-0.54
	2nd	1.00 ± 0.56	0.25 ± 1.26	**0.02**	-0.80
	3rd	1.04 ± 0.79	0.35 ± 1.21	0.05	-0.68
	All votes	0.91 ± 0.61	0.15 ± 1.26	< **0.001**†	-0.75
Thermal Comfort (Whole-body)	Pre	0.04 ± 1.01	0.00 ± 1.18	0.92	-0.03
	Right-after	0.04 ± 1.01	0.42 ± 1.20	0.31	0.35
	1st	0.04 ± 1.26	0.25 ± 1.36	0.63	0.16
	2nd	-0.04 ± 1.44	0.25 ± 1.39	0.55	0.20
	3rd	-0.09 ± 1.47	-0.31 ± 1.39	0.41	-0.28
	All votes	0.03 ± 1.23	0.15 ± 1.31	0.58†	0.07
Thermal Comfort (Upper-Back)	Pre	0.56 ± 1.23	0.54 ± 1.35	0.96	-0.015
	Right-after	0.56 ± 1.23	0.50 ± 1.25	0.88	-0.05
	1st	0.32 ± 1.34	0.12 ± 1.02	0.64	-0.15
	2nd	0.32 ± 1.55	0.21 ± 1.32	0.83	-0.07
	3rd	0.02 ± 1.31	0.04 ± 1.34	0.95	0.02
	All votes	0.35 ± 1.32	0.21 ± 1.22	0.70	-0.05
Thermal Acceptability (Whole-body)	Pre	0.61 ± 1.30	0.65 ± 1.05	0.94	0.03
	Right-after	0.61 ± 1.30	0.69 ± 1.12	0.86	0.06
	1st	0.61 ± 1.30	0.60 ± 1.16	0.95	0.02
	2nd	0.58 ± 1.47	0.65 ± 1.38	0.72	0.12
	3rd	0.47 ± 1.51	0.19 ± 1.40	0.74	-0.11
	All votes	0.52 ± 1.36	0.53 ± 1.26	0.90†	0.02
Thermal Acceptability (Upper-Back)	Pre	0.75 ± 1.31	0.75 ± 0.99	0.99	-0.04
	Right-after	0.75 ± 1.31	1.00 ± 1.04	0.55	0.08
	1st	0.65 ± 1.36	0.92 ± 1.01	0.52	-0.15

	2nd	0.79 ± 1.54	0.54 ± 1.37	0.62	-0.11
	3rd	0.26 ± 1.35	0.40 ± 1.43	0.78	-0.20
	All votes	0.64 ± 1.36	0.71 ± 1.22	0.65†	0.06
Thermal Preference (Whole-body)	Pre	-0.84 ± 1.15	-1.25 ± 1.17	0.43†	-0.35
	Right-after	-0.84 ± 1.15	-1.23 ± 1.13	0.49†	-0.34
	1st	-0.82 ± 1.13	-1.23 ± 1.15	0.44	-0.35
	2nd	-0.93 ± 1.05	-1.33 ± 1.09	0.27	-0.38
	3rd	-0.93 ± 1.15	-1.42 ± 0.93	0.18	-0.46
	All votes	-0.87 ± 1.10	-1.30 ± 1.06	0.29	-0.38
Thermal Preference (Upper-Back)	Pre	-1.00 ± 0.81	-1.04 ± 1.08	0.38†	-0.04
	Right-after	-1.00 ± 0.81	-0.92 ± 1.24	0.81	0.08
	1st	-0.95 ± 0.86	-1.10 ± 1.21	0.49†	-0.15
	2nd	-1.00 ± 0.87	-1.12 ± 1.32	0.73	-0.11
	3rd	-1.09 ± 0.87	-1.29 ± 1.12	0.55	-0.20
	All votes	-1.00 ± 0.83	-1.10 ± 1.20	0.56†	-0.09

†:Mann-Whitney non-parametric results, while rest refers to the T-test parametric results

Table A7.2 Statistical summary of the whole body and local thermal evaluation for female participants

Responses to the survey		Mean ± SD		P-value	Cohen's d
		Control Group	Local Cooling Group		
Thermal Sensation (Whole-body)	Pre	1.33 ± 0.54	1.45 ± 0.43	0.21†	0.25
	Right-after	1.33 ± 0.54	1.17 ± 0.60	0.48	-0.29
	1st	1.48 ± 0.79	1.55 ± 0.71	0.84	0.08
	2nd	1.88 ± 0.76	1.24 ± 0.92	0.07	-0.75
	3rd	1.61 ± 1.17	1.69 ± 0.77	0.83	0.09
	All votes	1.53 ± 0.79	1.41 ± 0.77	0.30†	-0.14
Thermal	Pre	0.55 ± 0.78	0.50 ± 0.76	0.88	-0.06

Sensation (Upper Back)	Right-after	0.55 ± 0.78	-0.50 ± 1.50	**0.04***	-0.84
	1st	0.91 ± 0.56	-0.05 ± 1.40	**0.04***	-0.85
	2nd	1.30 ± 0.99	-0.05 ± 1.40	**0.01***	-1.08
	3rd	1.30 ± 1.12	0.26 ± 1.57	0.07	-0.74
	All votes	1.01 ± 0.86	-0.08 ± 1.45	< **0.001**†	-0.75
Thermal Comfort (Whole-body)	Pre	0.12 ± 0.89	0.24 ± 0.93	0.75	0.12
	Right-after	0.12 ± 0.89	-0.02 ± 1.17	0.73	-0.13
	1st	-0.27 ± 1.58	-0.38 ± 1.34	0.85	-0.07
	2nd	-0.82 ± 1.73	-0.14 ± 1.67	0.33	0.40
	3rd	-0.42 ± 1.98	-0.40 ± 1.55	0.97	0.01
	All votes	-0.25 ± 1.47	-0.24 ± 1.41	0.71	0.07
Thermal Comfort (Upper Back)	Pre	0.79 ± 1.69	0.64 ± 0.85	0.78	-0.11
	Right-after	0.79 ± 1.69	-0.14 ± 1.17	0.12	-0.64
	1st	0.30 ± 1.31	-0.02 ± 1.22	0.52	-0.17
	2nd	-0.18 ± 1.49	-0.05 ± 1.18	0.80	-0.13
	3rd	-0.09 ± 1.75	-0.29 ± 1.47	0.76	-0.07
	All votes	0.32 ± 1.59	-0.12 ± 1.23	0.24	-0.05
Thermal Acceptability (Whole-body)	Pre	0.52 ± 1.09	0.64 ± 1.07	0.77	0.12
	Right-after	0.52 ± 1.09	0.31 ± 1.12	0.65	-0.18
	1st	-0.06 ± 1.16	0.00 ± 1.41	0.91	0.05
	2nd	-0.24 ± 1.56	0.29 ± 1.51	0.40	0.34
	3rd	-0.24 ± 1.95	-0.19 ± 1.81	0.94	0.03
	All votes	0.10 ± 1.40	0.10 ± 1.46	0.71	0.02
Thermal Acceptability (Upper Back)	Pre	1.12 ± 1.37	0.64 ± 0.90	0.30	-0.42
	Right-after	1.12 ± 1.37	0.31 ± 1.17	0.12	-0.64
	1st	0.48 ± 1.16	0.26 ± 1.36	0.67	-0.17
	2nd	0.39 ± 1.50	0.21 ± 1.36	0.75	-0.13
	3rd	0.18 ± 1.63	0.07 ± 1.48	0.86	-0.07
	All votes	0.66 ± 1.41	0.21 ± 1.31	0.23	0.06

Thermal Preference (Whole-body)	Pre	-1.52 ± 1.05	-0.45 ±	0.30	0.93
	Right-after	-1.52 ± 1.05	-0.60 ± 1.01	**0.03***	0.90
	1st	-1.61 ± 1.19	-1.07 ± 1.13	0.26	0.46
	2nd	-1.73 ± 0.98	-0.93 ± 1.38	0.11	0.65
	3rd	-1.61 ± 1.30	-1.07 ± 1.32	0.32	0.41`
	All votes	-1.59 ± 1.07	-0.92 ± 1.20	< **0.001**†***	-0.38
Thermal Preference (Upper Back)	Pre	-0.73 ± 0.93	-	0.67	0.17
	Right-after	-0.73 ± 0.93	-0.48 ± 0.97	0.52	0.26
	1st	-0.91 ± 1.20	-0.93 ± 1.16	0.97	-0.02
	2nd	-1.36 ± 1.28	-0.81 ± 1.09	0.25	0.47
	3rd	-1.03 ± 1.12	-0.90 ± 1.20	0.79	0.11
	All votes	-0.95 ± 1.08	-0.77 ± 1.09	0.30	-0.09

†:Mann-Whitney non-parametric results, while rest refers to the T-test parametric results

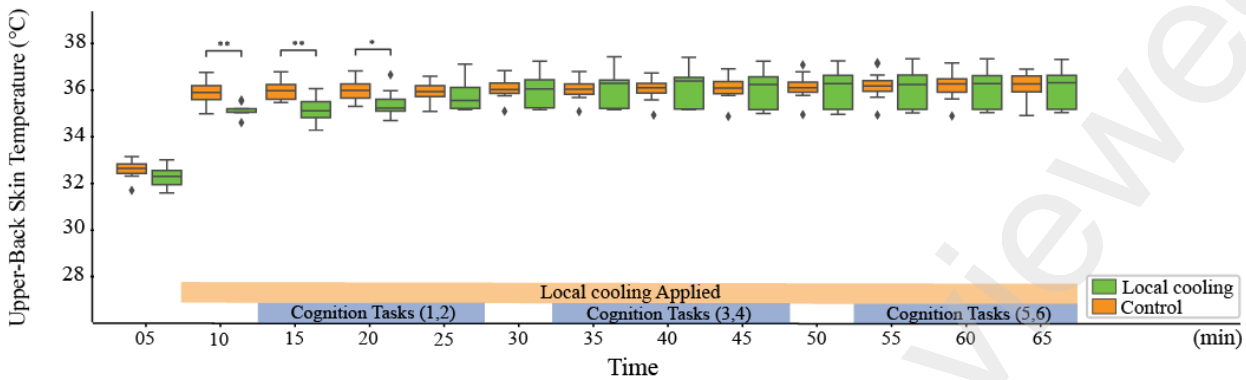
A.7.2. Skin Temperature

Upper Back Skin Temperature:

To further investigate the effect of gender on thermal sensation, we analyze the skin temperature data for both male and female participants. Looking at the males' skin temperature data, we see that the temperature drops significantly for the first 20 min before rising above the baseline for the rest of the experiment.

Furthermore, results showed that the same pattern for female participants as well for the first 20 min, but the temperature stabilized below the baseline for the rest of the experiment, which shows that the female participants were cooler in the upper back area compared to the male participants.

a) Upper-Back thermal sensation for male participants



b) Upper-Back thermal sensation for female participants

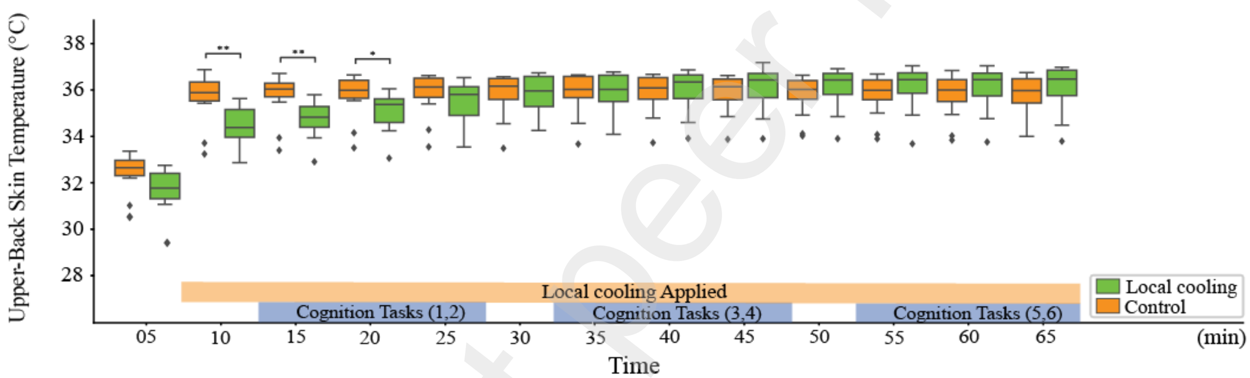
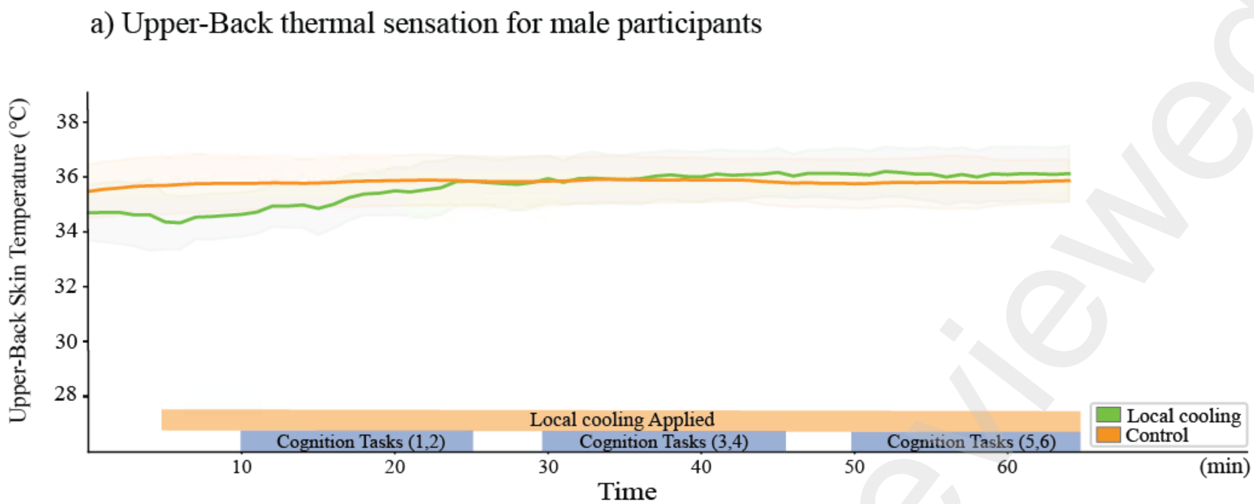


Figure A7.3 a) Upper-back skin temperature boxplot for male participant. Significant drop for the 20 min and then temperature stabilized below the baseline for the rest of the experiment. b) **Upper-back skin temperature Boxplot for female participants**. Significant statistical difference for the first 20 min.



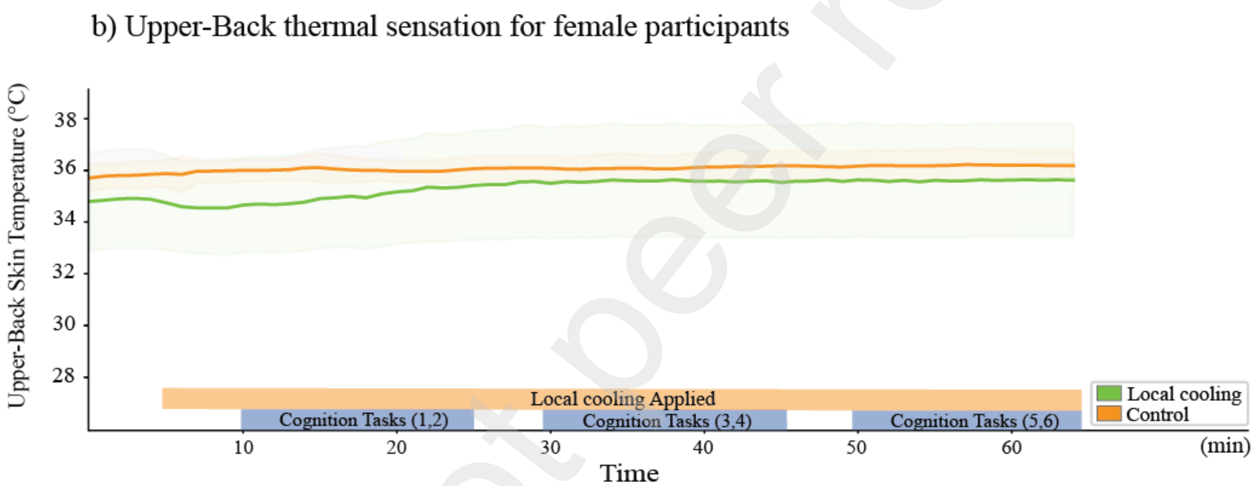


Figure A7.4 ***a)*** **Upper-back skin temperature plot for male participants**. Significant drop for the 20 min and then temperature rise above the baseline for the rest of the experiment; ***b)*** **Upper-back skin temperature plot for female participant**. Significant statistical difference for the first 20 min

A.7.3. Emotional Evaluation

Male Participants:

Table A7.3 PANAS-SF Statistical analysis results for male participants

Emotional State		Mean (SD)		P-value	Cohen's d
		Control Group	Local Cooling Group		
Positive Emotions	Determined	3.64 ± 1.13	3.69 ± 0.89	$0.47^{\dagger}$	0.05
	Attentive	3.46 ± 1.16	3.65 ± 1.26	$0.13^{\dagger}$	0.16

	Alert	3.29 ± 1.23	3.47 ± 1.41	0.15†	0.10
	Inspired	2.93 ± 1.42	3.16 ± 1.40	0.18†	0.09
	Active	3.12 ± 1.28	3.29 ± 1.40	0.20†	0.16
	Overall Positive Emotion	3.29 ± 1.07	3.45 ± 1.13	0.16†	-0.28
Negative Emotions	Afraid	1.25 ± 0.60	1.10 ± 0.35	0.05†	-0.07
	Nervous	1.47 ± 0.75	1.38 ± 0.65	0.29†	-0.44
	Upset	1.46 ± 0.77	1.15 ± 0.36	**0.004**† **	-0.27
	Ashamed	1.12 ± 0.33	1.04 ± 0.21	**0.044**† *	-0.20
	Hostile	1.25 ± 0.60	1.12 ± 0.32	0.127	0.13
	Overall Negative Emotion	1.33 ± 0.41	1.16 ± 0.23	**0.021**† *	-0.36

†:Mann-Whitney non-parametric results, while rest refers to the T-test parametric results

Female Participants:

Table A7.4 PANAS-SF Statistical analysis results for female participants

Emotional State		Mean (SD)		P-value	Cohen's d
		Control Group	**Local Cooling Group**		
Positive Emotions	Determined	2.75 ± 1.16	2.95 ± 1.17	0.20	0.10
	Attentive	2.77 ± 1.18	3.21 ± 1.12	**0.03** *	0.31
	Alert	2.75 ± 1.16	3.05 ± 1.02	0.07	0.13
	Inspired	2.09 ± 0.80	2.14 ± 1.05	0.49	-0.02
	Active	2.61 ± 1.15	2.25 ± 1.21	**0.04** *	0.41
	Overall Positive	2.60 ± 0.94	2.72 ± 0.97	0.51	-0.47

	Emotion				
Negative Emotions	Afraid	1.27 ± 0.59	1.07 ± 0.26	**0.02** *	-0.21
	Nervous	1.64 ± 0.72	1.50 ± 0.89	**0.046** *	-0.56
	Upset	1.39 ± 0.65	1.16 ± 0.37	0.03 *	0.12
	Ashamed	1.05 ± 0.21	1.11 ± 0.31	0.13	-0.68
	Hostile	1.25 ± 0.49	1.02 ± 0.13	**0.0005** ***	0.03
	Overall Negative Emotion	1.32 ± 0.39	1.17 ± 0.60	**0.02** *	-0.53

†:Mann-Whitney non-parametric results, while rest refers to the T-test parametric results

A.7.4. Cognitive Performance

The different cognitive tasks with the gender effect were analyzed using the same metrics between the two experimental conditions. Similar to the overall analysis, participants performed better on one task (BART) of the six cognitive tasks when the local cooling was applied, only this time, only male participant showed a difference in risk taking ($p = 0.001$). On the other hand, female participants showed no major difference between the two experimental group.

We can say that the male participants in the local cooling group showed more risk-taking behavior while feeling more comfortable compared to the female participants, who despite feeling more cooler than the control group, they haven't shown any risk-taking behavior increase.

Cognitive Tasks Results :

Table A7.5 *Statistical Analysis summary of the cognitive tasks based on gender effect*

Cognitive Test	Cognition Function	Evaluation Metric	P-Value		
			Overall Group	Male Group	Female Group
Token Test	Working Memory	Percent accuracy	0.45	0.91	0.20
Stroop Color Test	Response Inhibition (Reaction Time)	Proportion Correct	0.17†	0.27	0.23†
		Reaction Time (ms)	0.45†	0.44	0.26
Spatial Processing Test	Short Term Memory	Proportion correct (0-deg)	0.41	0.58	0.39
		Proportion correct (90-deg)	0.35†	0.14	0.74
		Proportion correct (180-deg)	0.41†	0.79	0.78
		Reaction time (ms)	0.1†	0.94	0.08
BART Balloon Test	Risk Taking	Total explosions	0.13	0.07	0.93
		Adjusted Total Pump Count	**0.0027** ***	**0.001** ***	0.67
		Average adjusted Pump Count	0.67	0.98	0.44
AX-CPT	Attention	Proportion correct	0.19†	0.48	0.19
		Reaction time (ms)	0.18†	0.23	0.61
Alternative User Task	Creativity	Average Score	0.39†	0.96	0.43†

†:Mann-Whitney non-parametric results, while rest refers to the T-test parametric results

A.7.5. NASA-TLX Questionnaire

Male Participants

Table A7.6 NASA-TLX statistical analysis results for male participants

Task Load	Mean ± SD		P-value	Cohen's d
	Control Group	Local Cooling Group		
Mental Demand	4.34 ± 1.72	4.41 ± 1.74	0.92	0.04
Physical Demand	1.37 ± 1.23	1.77 ± 2.24	0.78†	0.22
Temporal Demand	4.25 ± 1.52	4.76 ± 1.26	0.50	0.36
Performance	4.81 ± 1.67	4.92 ± 1.08	0.66	0.08
Effort	3.99 ± 1.70	4.76 ± 1.12	0.19	0.54
Frustration	3.76 ± 1.55	3.31 ± 1.80	0.51	-0.26
Total Task Load	3.76 ± 0.93	3.99 ± 0.68	0.47	0.29

†: Mann-Whitney non-parametric results, while rest refers to the T-test parametric results

Female Participants

Table A7.7 NASA-TLX statistical analysis results for female participants

Task Load	Mean ± SD		P-value	Cohen's d
	Control Group	Local Cooling Group		
Mental Demand	4.31 ± 1.33	5.05 ± 0.88	0.23	0.63
Physical Demand	0.78 ± 1.17	1.95 ± 1.65	0.23†	0.83
Temporal Demand	3.77 ± 2.13	3.95 ± 1.47	0.85	0.09
Performance	4.98 ± 1.50	4.85 ± 1.48	0.74	-0.08
Effort	4.39 ± 1.79	4.70 ± 0.69	0.21	0.21
Frustration	4.90 ± 1.00	3.55 ± 1.56	0.05	-1.06
Total Task Load	4.22 ± 0.63	4.01 ± 0.73	0.71	0.19

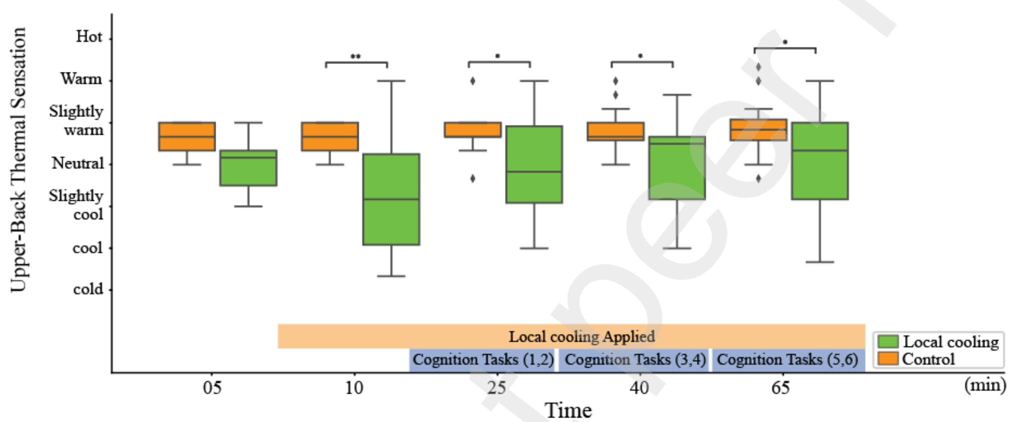
†:Mann-Whitney non-parametric results, while rest refers to the T-test parametric results

A.8. Initial Thermal Sensation Effect

A.8.1. Thermal Evaluation

Upper-Back Thermal sensation

Comparing the local thermal sensation between the control group and the local cooling group, cool participants showed a drop in the local thermal sensation right after the local cooling was applied and throughout the experiment period line, showing a significant difference ($p < 0.001$) between the control group (*1.04 ± 0.54*) and the local cooling group (*-0.10 ± 1.25*). Warm group also showed a statistical difference between the two experimental groups, but on the inequivalent scale, showing some difference at after the local cooling was applied and after the second cognitive trials, the overall vote showed significant difference between ($p < 0.001$) the control group (*1.54 ± 0.87*) and the experimental group (*0.16 ± 1.43*). These results suggest that the cool group showed more effect of local thermal sensation than the warm group.



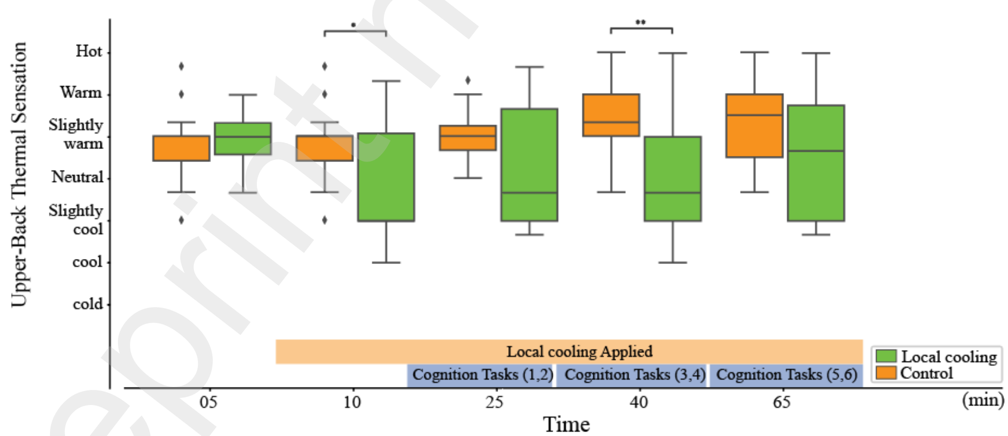


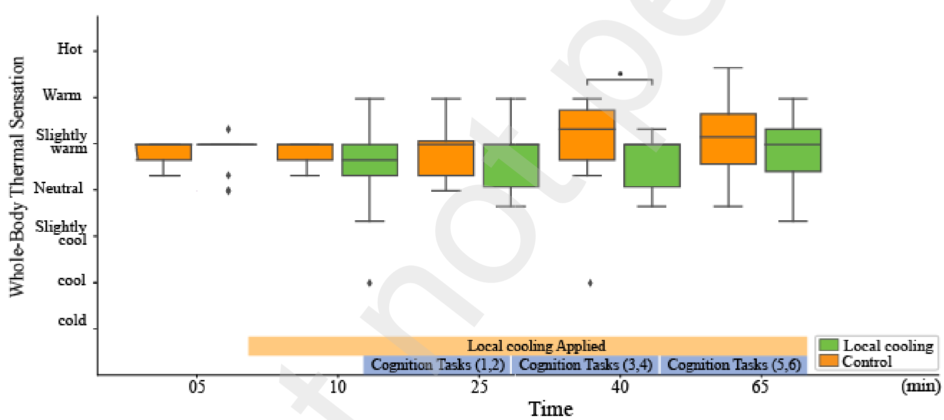
Figure A8.1 ***a) Upper-Back Thermal Sensation Boxplot for cool group participants***. *The second boxplot shows significant statistical difference in the thermal sensation for local cooling group (*p = 0.001*). The votes at cognitive tasks show a relative and significant statistical difference respectively (* p = 0.03) *for first test;* p = 0.02 *and* p = 0.03 *for second and third task).* ***b) Upper-Back Thermal Sensation***

***Boxplot for cool group participants**. The second boxplot shows a relative statistical difference in the thermal sensation for local cooling group (*p = 0.02*). The vote at the second cognitive task show a significant statistical difference (* p = 0.007).

Whole-body Thermal Sensation

Warm Participants showed a statistical difference in the whole-body thermal sensation (*p = 0.01*) right after the local cooling was applied, showing a drop of the local cooling group (*1.21 ± 0.64*) compared to the control group (1.74 ± 0.37). On the other hand, cool participants showed a statistical difference as well (*p = 0.02*), between the control group (*1.25 ± 0.64*), and the experimental (*0.55 ± 0.92*), only for the warm group the difference showed after the second cognitive trials. This may suggest that the local cooling effect was higher and quicker to the warm group than the cool group, although the cool group did show statistical difference later on, which tells that even for cool group, the local cooling strategy did have a positive impact on both group on different timeframe, one faster than the other.

a) Whole-Body thermal sensation for cool participant



b) Whole-Body thermal sensation for warm participant

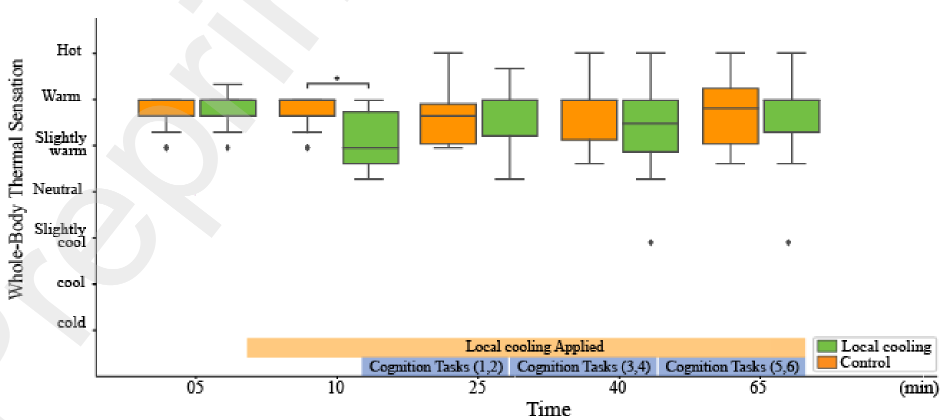


Figure A8.2 ***a)*. *Whole-Body Thermal Sensation Boxplot for cool group participants*.** *The second test boxplot shows significant statistical difference in the thermal sensation for local cooling group (*p = 0.02*).*
b) Whole-Body Thermal Sensation Boxplot for warm group participants. *The second boxplot shows significant statistical difference in the thermal sensation for local cooling group (*p = 0.02*).*

Results of statistical tests

Table A8.1 Statistical summary of the whole body and local thermal evaluation for cool group

Responses to the survey		Mean ± SD		P-value	Cohen's d
		Control Group	Local Cooling Group		
Thermal Sensation (Whole-body)	Pre	0.83 ± 0.24	0.84 ± 0.39	0.23†	0
	Right-after	0.83 ± 0.24	0.52 ± 0.95	0.23†	-0.45
	1st	0.94 ± 0.64	0.76 ± 0.82	0.47	-0.27
	2nd	1.25 ± 0.64	0.55 ± 0.92	**0.02†**	-0.90
	3rd	1.12 ± 0.80	0.95 ± 0.92	0.55	-0.22
	All votes	1.38 ± 0.59	0.69 ± 0.84	0.01	-0.40
Thermal Sensation (Upper Back)	Pre	0.62 ± 0.32	0.00 ± 0.68	0.2	-1.20
	Right-after	0.62 ± 0.32	-0.64 ± 1.39	**0.001**	-1.30
	1st	0.77 ± 0.48	0.05 ± 1.23	**0.03**	-0.79
	2nd	0.83 ± 0.52	0.07 ± 1.11	**0.02**	-0.89
	3rd	0.92 ± 0.73	0.12 ± 1.24	**0.03**	-0.80
	All votes	1.04 ± 0.54	-0.10 ± 1.25	**< 0.001**	-0.96
Thermal Comfort (Whole-body)	Pre	0.44 ± 0.98	0.62 ± 0.89	0.78	0.19
	Right-after	±	0.74 ± 1.21	0.60	0.27
	1st	0.42 ± 1.45	0.62 ± 1.20	0.92	0.15
	2nd	0.19 ± 1.62	0.48 ± 1.20	0.75	0.20
	3rd	0.44 ± 1.76	0.21 ± 1.16	0.49	-0.15
	All votes	0.49 ± 1.67	0.51 ± 1.17	0.56	0.12
Thermal	Pre	1.10 ± 1.13	1.33 ± 0.92	0.81	0.22

Comfort (Upper Back)	Right-after	1.10 ± 1.13	0.48 ± 1.34	0.12	-0.51
	1st	0.81 ± 1.25	0.43 ± 1.03	0.23	-0.33
	2nd	0.71 ± 1.40	0.50 ± 0.93	0.48	-0.17
	3rd	0.50 ± 1.22	0.26 ± 1.03	0.33	-0.21
	All votes	1.04 ± 0.54	0.41 ± 1.07	0.09	-0.21
Thermal Acceptability (Whole-body)	Pre	0.88 ± 0.98	1.07 ± 0.78	0.81	0.22
	Right-after	0.88 ± 0.98	0.93 ± 1.09	0.97	0.05
	1st	0.60 ± 1.31	0.69 ± 1.20	0.92	0.07
	2nd	0.67 ± 1.49	0.93 ± 1.04	0.74	0.20
	3rd	0.44 ± 1.59	0.60 ± 1.06	0.94	0.11
	All votes	0.86 ± 1.66	0.78 ± 1.08	0.53	0.13
Thermal Acceptability (Upper Back)	Pre	1.23 ± 1.16	1.19 ± 0.71	0.65	-0.04
	Right-after	1.23 ± 1.16	0.90 ± 1.24	0.33	-0.27
	1st	0.94 ± 1.32	0.93 ± 1.09	0.80	-0.007
	2nd	1.19 ± 1.42	0.90 ± 0.99	0.34	-0.22
	3rd	0.54 ± 1.26	0.67 ± 1.01	0.90	0.10
	All votes	1.29 ± 1.56	0.85 ± 1.06	0.57	-0.09
Thermal Preference (Whole-body)	Pre	-0.83 ± 0.63	-0.36 ± 1.30	0.29	0.48
	Right-after	-0.83 ± 0.63	-0.57 ± 1.19	0.44	0.28
	1st	-0.87 ± 0.81	-0.71 ± 1.15	0.73	0.16
	2nd	-0.98 ± 0.88	-0.62 ± 1.25	0.58	0.34
	3rd	-1.02 ± 1.06	-0.79 ± 1.17	0.79	0.21
	All votes	-1.24 ± 1.03	-0.67 ± 1.16	0.17	0.30
Thermal Preference (Upper Back)	Pre	-0.58 ± 0.58	-0.62 ± 0.89	0.64	-0.05
	Right-after	-0.58 ± 0.58	-0.55 ± 1.18	0.82	0.04
	1st	-0.65 ± 0.68	-0.67 ± 1.09	0.79	-0.02
	2nd	-0.77 ± 1.02	-0.69 ± 1.01	0.91	0.08
	3rd	-0.67 ± 0.75	-0.79 ± 1.10	0.52	-0.13

	All votes	-0.89 ± 0.90	-0.67 ± 1.07	0.97	-0.01

†:Mann-Whitney non-parametric results, while rest refers to the T-test parametric results

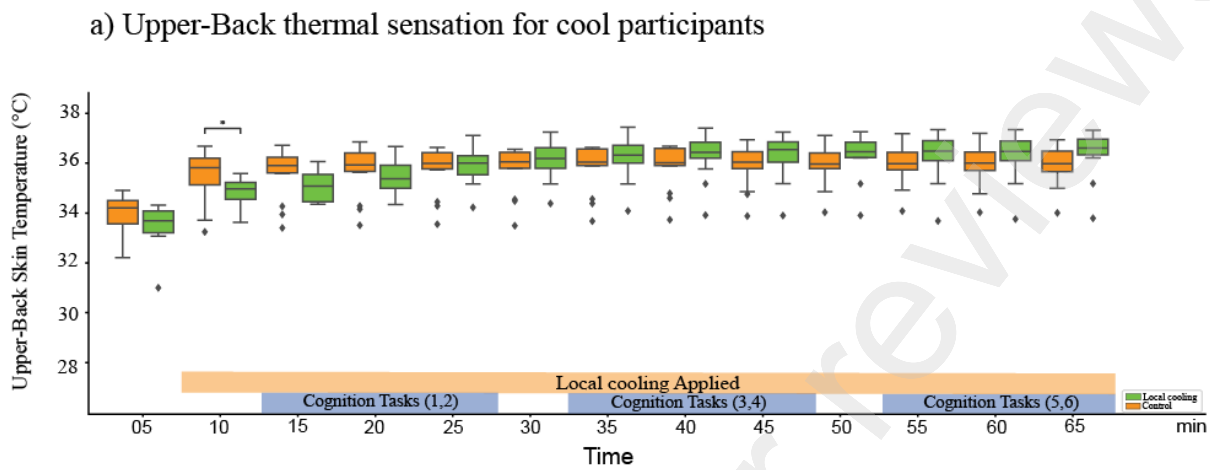
Table A8.2 Statistical summary of the whole body and local thermal evaluation for warm group

Responses to the survey		**Mean ± SD**		**P-value**	**Cohen's d**
		Control Group	**Local Cooling Group**		
Thermal Sensation (Whole-body)	Pre	1.74 ± 0.37	1.81 ± 0.34	0.30†	0.20
	Right-after	1.74 ± 0.37	1.21 ± 0.64	0.01†	-0.99
	1st	1.62 ± 0.55	1.67 ± 0.68	0.83	0.07
	2nd	1.76 ± 0.78	1.40 ± 1.02	0.28	-0.40
	3rd	1.62 ± 1.00	1.83 ± 0.66	0.49	0.25
	All votes	2.24 ± 0.69	1.52 ± 0.78	0.25†	-0.16
Thermal Sensation (Upper Back)	Pre	0.83 ± 0.89	0.90 ± 0.66	0.83	-0.08
	Right-after	-	-0.23 ± 1.41	**0.02**	-0.88
	1st	1.00 ± 0.61	0.27 ± 1.41	0.08	-0.65
	2nd	1.43 ± 0.85	0.15 ± 1.50	**0.008**	-1.03
	3rd	1.38 ± 1.07	0.48 ± 1.49	0.07	-0.69
	All votes	1.54 ± 0.87	0.16 ± 1.43	< 0.001	-0.67
Thermal Comfort (Whole-body)	Pre	-0.36 ± 0.74	-0.33 ± 1.01	0.94	0.03
	Right-after	-	-0.25 ± 0.97	0.74	0.12
	1st	-0.64 ± 1.04	-0.62 ± 1.25	0.97	0.01
	2nd	-0.90 ± 1.34	-0.29 ± 1.69	0.28	0.40
	3rd	-0.71 ± 1.34	-0.85 ± 1.46	0.78	-0.10
	All votes	-0.87 ± 1.29	-0.50 ± 1.36	0.51	0.10
Thermal Comfort (Upper	Pre	0.12 ± 1.52	-0.06 ± 0.87	0.69	-0.15
	Right-after	-	-0.04 ± 1.12	0.74	-0.12

Back)	1st	-0.26 ± 1.16	-0.27 ± 1.08	0.98	-0.01
	2nd	-0.52 ± 1.41	-0.27 ± 1.39	0.63	0.18
	3rd	-0.62 ± 1.52	-0.44 ± 1.59	0.75	0.12
	All votes	-0.42 ± 1.66	-0.25 ± 1.29	0.79	0.01
Thermal Acceptability (Whole-body)	Pre	0.24 ± 1.39	0.27 ± 1.12	0.94	0.03
	Right-after	-	0.15 ± 1.04	0.84	-0.07
	1st	0.05 ± 1.30	0.00 ± 1.33	0.92	-0.03
	2nd	-0.31 ± 1.42	0.08 ± 1.64	0.49	0.25
	3rd	-0.21 ± 1.77	-0.50 ± 1.82	0.68	-0.16
	All votes	-0.07 ± 1.71	-0.06 ± 1.47	0.97	-0.01
Thermal Acceptability (Upper Back)	Pre	0.50 ± 1.42	0.27 ± 0.90	0.60	-0.19
	Right-after	-	0.48 ± 1.05	0.96	-0.01
	1st	0.19 ± 1.12	0.33 ± 1.28	0.75	0.12
	2nd	0.02 ± 1.40	-0.06 ± 1.49	0.87	-0.06
	3rd	-0.12 ± 1.57	0.13 ± 1.67	0.99	-0.004
	All votes	0.19 ± 1.65	0.16 ± 1.38	0.98	-0.03
Thermal Preference (Whole-body)	Pre	-1.38 ± 1.51	-1.33 ± 1.00	0.92	0.03
	Right-after	-	-1.25 ± 0.95	0.11†	0.10
	1st	-1.38 ± 1.51	-1.54 ± 0.99	0.37†	-0.12
	2nd	-1.50 ± 1.25	-1.60 ± 1.04	0.43†	-0.09
	3rd	-1.36 ± 1.42	-1.67 ± 0.93	0.48	-0.26
	All votes	-0.08 ± 1.71	-1.51 ± 0.97	0.61†	-0.07
Thermal Preference (Upper Back)	Pre	-1.26 ± 0.98	-1.02 ± 0.93	0.49	0.25
	Right-after	-	-0.85 ± 1.09	0.29	0.39
	1st	-1.26 ± 1.18	-1.33 ± 1.19	0.87	-0.06
	2nd	-1.55 ± 0.90	-1.23 ± 1.34	0.46	0.27
	3rd	-1.52 ± 0.97	-1.40 ± 1.16	0.74	0.12
	All votes	-1.86 ± 1.25	-1.20 ± 1.18	0.33†	0.19

A.8.2. Skin Temperature

Upper Back Skin Temperature



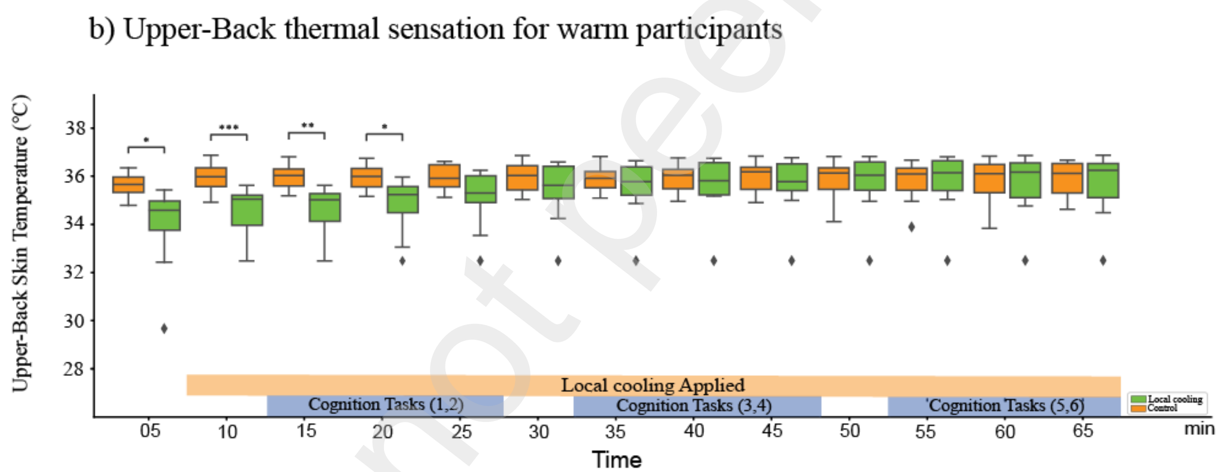


Figure A8.3 a) Upper-back skin temperature boxplot for the cool group. Significant at the 10 min window. **b) Upper-back skin temperature Boxplot for the warm group**. Significant statistical difference for the first 20 min.

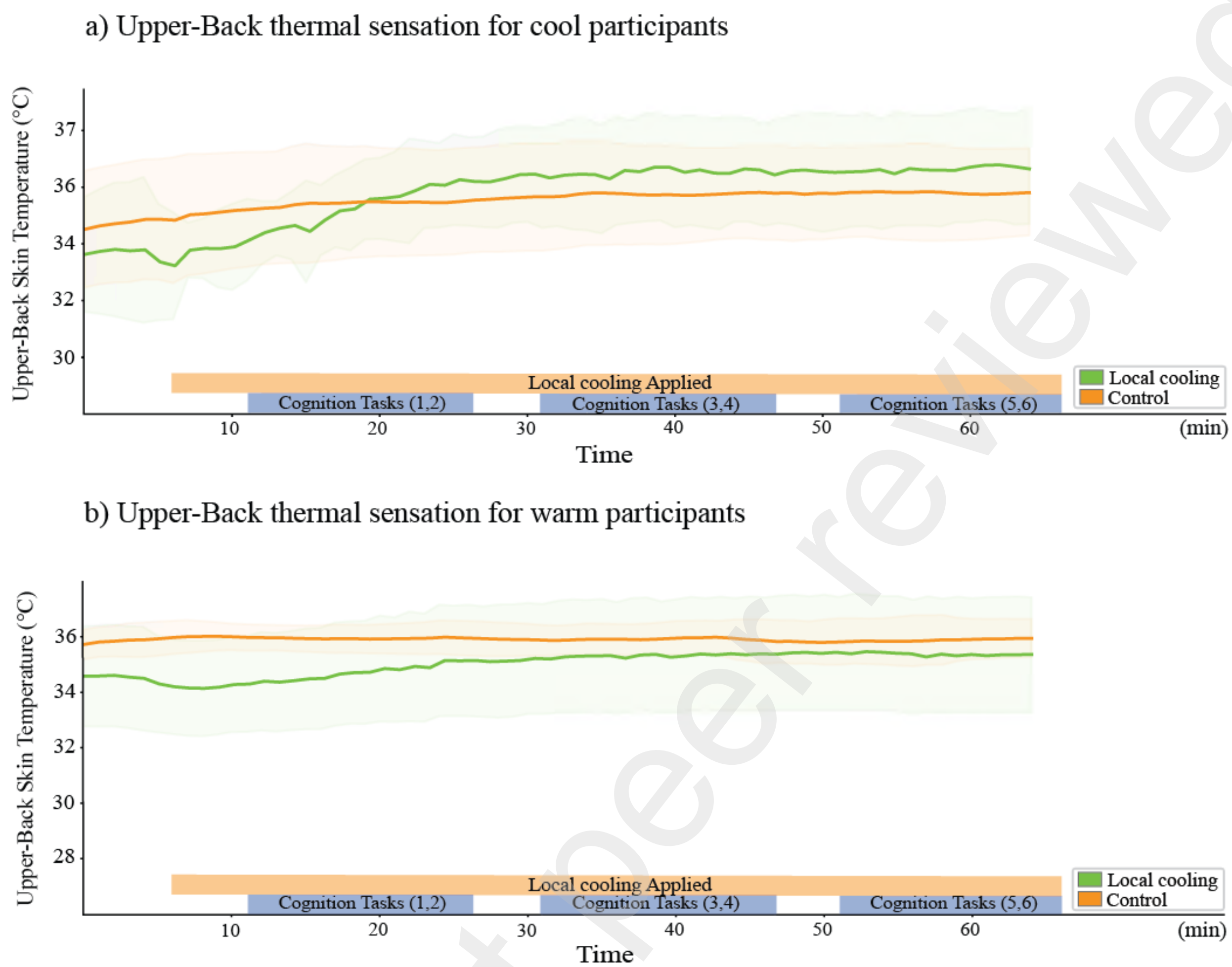


Figure A8.4 a) Upper-back skin temperature plot for the cool group. Significant drop for the 20 min and then temperature rise above the baseline for the rest of the experiment for the cool participants; **b) Upper-back skin temperature plot for the cool participants**. Significant statistical difference for the first 20 min and remained slightly lower than the control group.

A.8.3. Emotional Evaluation

Analysis Results

Cool Group

Table A8.3 PANAS-SF Statistical analysis results for the cool group

Emotional State	Mean (SD)		P-value	Cohen's d
	Control Group	Local Cooling Group		

Positive Emotions	Determined	3.38 ± 1.03	3.64 ± 0.88	0.07†	0.26
	Attentive	3.34 ± 1.00	3.93 ± 0.99	0.001† **	0.58
	Alert	3.25 ± 1.17	3.70 ± 1.08	0.02† *	0.35
	Inspired	2.78 ± 1.15	3.07 ± 1.26	0.07†	0.21
	Active	2.95 ± 1.13	3.30 ± 1.23	0.06†	0.33
	Overall Positive Emotion	3.14 ± 0.88	3.53 ± 0.91	0.02*	0.51
Negative Emotions	Afraid	1.22 ± 0.63	1.11 ± 0.31	0.33†	-0.25
	Nervous	1.39 ± 0.68	1.46 ± 0.76	0.27†	0.05
	Upset	1.28 ± 0.55	1.12 ± 0.33	0.05†	-0.21
	Ashamed	1.08 ± 0.27	1.09 ± 0.29	0.41†	-0.01
	Hostile	1.05 ± 0.21	1.09 ± 0.29	0.17†	0.29
	Overall Negative Emotion	1.20 ± 0.35	1.18 ± 0.23	0.35†	-0.08

†: Mann-Whitney non-parametric results, while rest refers to the T-test parametric results

Warm Group

Table A8.4 PANAS-SF Statistical analysis results for the warm group

	Emotional State	**Mean (SD)**		**P-value**	**Cohen's d**
		Control Group	**Local Cooling Group**		
Positive Emotions	Determined	3.21 ± 1.41	3.23 ± 1.09	0.30	-0.11
	Attentive	3.04 ± 1.41	3.13 ± 1.21	0.49	-0.01
	Alert	2.91 ± 1.28	2.98 ± 1.31	0.49†	-0.08
	Inspired	2.43 ± 1.45	2.47 ± 1.31	0.48†	-0.10
	Active	2.88 ± 1.40	2.50 ± 1.44	0.02† *	-0.41

	Overall Positive Emotion	2.89 ± 1.27	2.86 ± 1.13	0.30†	-0.17
Negative Emotions	Afraid	1.29 ± 0.53	1.07 ± 0.31	0.002† **	-0.42
	Nervous	1.70 ± 0.76	1.40 ± 0.81	0.003† **	-0.34
	Upset	1.61 ± 0.85	1.13 ± 0.34	< 0.001† ***	-0.78
	Ashamed	1.11 ± 0.31	1.07 ± 0.25	0.19†	-0.18
	Hostile	1.46 ± 0.71	1.07 ± 0.25	<0.001† ***	-0.74
	Overall Negative Emotion	1.43 ± 0.412	1.11 ± 0.24	<0.001† ***	-0.79

†: Mann-Whitney non-parametric results, while rest refers to the T-test parametric results

A.8.4. Cognitive Performance

Cognitive Performance Results

The results showed the cool group performance better on two cognitive tasks (BART for Risk Taking and AX-CPT for Attention) of the six cognitive tasks. For the BART risk taking task, the cool group condition showed a difference in risk taking behavior ($p = 0.03$) compared to the warm group who hasn't show any significant difference between to the experimental condition. Furthermore, we see that the cool group showed significance in the reaction time of the AX-CPT attention task (p = 0.03). The results of the rest of the cognitive tasks did not show any significant difference for both groups. This suggests that the cool participants in the local cooling group showed more risk-taking behavior while feeling more comfortable compared to the warm participants. Furthermore, the cool group showed more increase in attention which resulted in shorted reaction time.

Table A8.5 Statistical analysis summary of the cognitive tasks based on initial thermal sensation vote

Cognitive Test	Cognition Function	Evaluation Metric	P-Value		
			Overall Group	Cool Group	Warm Group
Token Test	Working Memory	Percent accuracy	0.45	0.88	0.17

Stroop Color Test	Response Inhibition (Reaction Time)	Proportion Correct	0.17†	0.96	0.09
		Reaction Time (ms)	0.45†	0.22	0.0502
Spatial Processing Test	Short Term Memory	Proportion correct (0-deg)	0.41	0.25	0.88
		Proportion correct (90-deg)	0.35†	0.22	0.96
		Proportion correct (180-deg)	0.41†	0.67	0.68†
		Reaction time (ms)	0.1†	0.29	0.64
BART Balloon Test	Risk Taking	Total explosions	0.13	0.27	0.24
		Adjusted Total Pump Count	0.0027 ***	0.03	0.28
		Average adjusted Pump Count	0.67	0.50	0.82
AX-CPT	Attention	Proportion correct	0.19†	0.43†	0.23†
		Reaction time (ms)	0.18†	0.03 *	0.80
Alternative User Task	Creativity	Average Score	0.39†	0.28	0.80

†: Mann-Whitney non-parametric results, while rest refers to the T-test parametric results

A.8.5. NASA-TLX Questionnaire

Cool Group

Table A8.6 NASA-TLX statistical analysis results for the cool groups

Task Load	Mean ± SD		P-value	Cohen's d
	Control Group	Local Cooling Group		

Mental Demand	4.44 ± 1.44	4.87 ± 1.11	0.74†	0.33
Physical Demand	1.62 ± 1.39	1.77 ± 1.70	0.96†	0.10
Temporal Demand	4.35 ± 1.65	5.02 ± 0.93	0.26†	0.50
Performance	4.64 ± 1.65	5.22 ± 0.73	0.75†	0.45
Effort	3.89 ± 1.67	5.10 ± 1.28	0.09†	0.80
Frustration	3.56 ± 1.50	3.32 ± 1.99	0.70	-0.14
Total Task Load	3.75 ± 0.90	4.22 ± 0.63	0.11	0.59

†:Mann-Whitney non-parametric results, while rest refers to the T-test parametric results

Warm Group:

Table A8.7 NASA-TLX statistical analysis results for the warm group

Task Load	**Mean ± SD**		**P-value**	**Cohen's d**
	Control Group	**Local Cooling Group**		
Mental Demand	4.40 ± 1.58	4.20 ± 1.59	0.73†	-0.12
Physical Demand	1.05 ± 1.36	1.36 ± 1.90	0.74†	0.18
Temporal Demand	3.97 ± 1.82	4.26 ± 1.46	0.63	0.18
Performance	4.87 ± 1.47	5.01 ± 1.35	0.98†	0.09
Effort	4.55 ± 1.72	4.86 ± 0.98	0.55	0.22
Frustration	4.55 ± 1.57	3.41 ± 1.86	0.08†	-0.65
Total Task Load	3.90 ± 0.97	3.85 ± 0.66	0.87	-0.06

†:Mann-Whitney non-parametric results, while rest refers to the T-test parametric results