Investigating User Experience of On-Body Heating Strategies in Indoor Environments

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FEATURE AT A GLANCE:
Thermal physiology and psychophysics are complex and nuanced, with significant variability between individuals. Wearable devices have the potential to offer customizable microclimate control. However, individual experiences with different supplemental heating strategies are likely to vary considerably in unconstrained environments. The physiological responses, psychophysical effects, and qualitative experiences of participants using five readily available heating strategies were collected in a quasi-field study environment (n=17). Although all devices maintained or increased fingertip temperature, effects observed from controlled studies of thermal physiology are not clearly seen. Physiological, perceptual, and experiential data are presented, exploring heating technologies and thermal comfort in typical indoor environments.

KEYWORDS:
heating technologies, thermal comfort, wearables, psychophysics, physiology

The experience of thermal comfort is influenced by a complex mix of physiological, psychological, physical, and environmental factors (Djongyang et al., 2010), and has significant influences on attention, cognition, and productivity (Zhang et al., 2017). However, achieving consistent thermal comfort for all individuals in a shared environment is challenging, due to the variability of individual thermal physiology and preferences (Richard & Gail Schiller, 1998). As few as 11% buildings have 80% or more participants expressing satisfactory thermal comfort (Huizenga et al., 2006), which affects motivation and performance (Cui et al., 2013) and gender equality (Irfan, 2015; Kingma & Van Marken Lichtenbelt, 2015).

On-body, wearable heating technologies are uniquely positioned to provide continuous, personalized modulation of an individual's microclimate, and may offer substantial energy savings, while allowing co-located individuals to personalize temperatures. Most research into wearable heating technologies is centered on extreme (e.g., (Brajkovic & Ducharme, 2002)) and/or tightly controlled (e.g., (Wang et al., 2007)) environments; and findings may not translate well to uncontrolled thermal and physiological contexts that are more representative of typical indoor experiences. Therefore, we are motivated to understand interpersonal variability in experience and physiological response for users in everyday indoor environments when using readily available wearable heating devices.

BACKGROUND

There are two commonly used indicators of human body temperature: (1) core temperature (that must remain within 32–40^{0}C to support life), and (2) temperatures at the periphery (that vary as heat is exchanged with the environment). In colder temperatures, peripheral blood vessels constrict, retaining warmed blood in the core, reducing heat loss; in warmer temperatures, these vessels dilate to dissipate body heat. Importantly, two somewhat independent feedback loops control these vascular mechanisms: a central loop responds to temperature of blood returning to the brain, and a local loop controls peripheral blood flow—meaning that the core may be adequately warm, while the local peripheral temperatures decrease with restricted access to heated blood (Giesbrecht & Wilkerson, 2006). Variability in thermal preference is influenced by individual thermal "set points" (i.e., comfortable temperatures); which are known to vary across populations, influenced by transient factors like circadian rhythms (Krauchi & Wirz-Justice, 1994; Refinetti & Menaker, 2010), or adaptation to a climate (Brager & de Dear, 1998). Thermal comfort relative to the set point has been shown to be influenced by temperatures at the periphery (Jacquot et al., 2014; Koscheyev et al., 2001; Koscheyev, Leon, et al., 2005). In thermoneutral temperatures, particularly on the cool side, temperatures at the periphery are known to be particularly volatile as vasomotor responses act to keep body temperatures stable (Parkinson & Dear, 2015; Wang et al., 2007); fingertip temperatures change in response to the body's rate of heat loss (Brajkovic & Ducharme, 2003). Models based on body measurements such as skin temperatures/heart rate have improved accuracy over commonly used metrics (e.g., Predicted Mean Vote (PMV) that is based on environmental parameters, metabolic rate, and clothing) (Kobiela et al., 2019). However, thermal comfort is also influenced by many additional individual factors including demographics and anthropometrics, as well as contextual factors like food intake, exercise, and menstrual cycle (Doherty & Arens, 1988). This complexity can make translation of the results of controlled laboratory investigations to real-world contexts challenging.

Modifications to thermal experience can either alter the ambient environment (Scott et al., 2011) or deliver a thermal stimulus to specific body regions (Akazue et al., 2016; Wilson et al., 2011). Here, we focus on technologies that *are* or *could be made* wearable, specifically for body heating in cool environments. Because of the importance of peripheral temperature on perceived thermal balance/comfort, several studies have considered the influence of heat delivered to different body areas on fingertip temperatures. Directly heating the fingers is a challenge for wearables used indoors, because of general resistance to indoor glove-wearing. Perhaps the most common approach is heating the wrists/hands (Koscheyev et al., 2001; Koscheyev, Coca, et al., 2005); however, other prior work has not successfully replicated these results (Dupler et al., 2019; Gagliardi et al., 2018). Another common approach is torso heating which has been shown to not only increase fingertip temperature (Bader & Macht, 1948) but also to maintain finger temperature better than directly heating the hands/fingers (this has been shown in −25°C temperatures (Brajkovic & Ducharme, 2002)). A less-studied but interesting approach is heating the face, which has been shown to induce temperature increase in the fingertips specifically (Bader & Macht, 1948). Effects were particularly pronounced in room-temperatures (23.5°C), but also effective (with smaller effects) in lower 15°C temperatures. However, these localized heating strategies have not been studied together in everyday indoor environments.

Here, we investigate the use of readily available heating devices in typical indoor climate-controlled environments: contexts in which some users may feel uncomfortably cool or cold. We explore everyday-usable mechanisms that allow delivery of heat to the periphery (fingers) without direct finger contact, and assess the variability observed in field-like contexts in relationships between heating strategy, fingertip temperature change, and comfort. Further, we explore user perception of wearable devices both in function (induced temperature changes) and in experience.

USER STUDY METHODS

A mixed-method study with a within-subjects experimental design and a focus group was conducted in May 2019, including 17 participants (6 female, 11 male, ages=20–49). The study was conducted in an indoor office–like environment with temperatures at 21–24°C, 27–29% humidity. All participants wore full-cover trousers, closed-toed shoes, and were provided cotton long-sleeve t-shirts. Trials were conducted with participants seated, engaged in self-directed desk work.

Thermal Stimulus Exposure Conditions

Each participant was exposed to a random sequence of five 15-minute heating conditions (Figure 1). Four out of five of the test conditions were representative commercial products most commonly available to consumers, and one was a custom-fabricated hand heating prototype (made according to Dupler et al., 2019), representative of an indoor-wearable heated glove technology. Participants spent approximately 30 minutes in each station for setup, thermal exposure, take-down, and cool-down time (cool-down mean = 16.25±5.5 minutes; variation due to station transition delays/hardware issues). Before testing, participants spent ~15 minutes in the test environment to allow body temperature stabilization (previous research such as Arens et al., (2006) found skin temperatures stabilized within ~10 minutes in a controlled environment). Temperatures were not measured between test conditions, but participants were randomized between conditions to help adjust for any lingering effects of prior conditions.

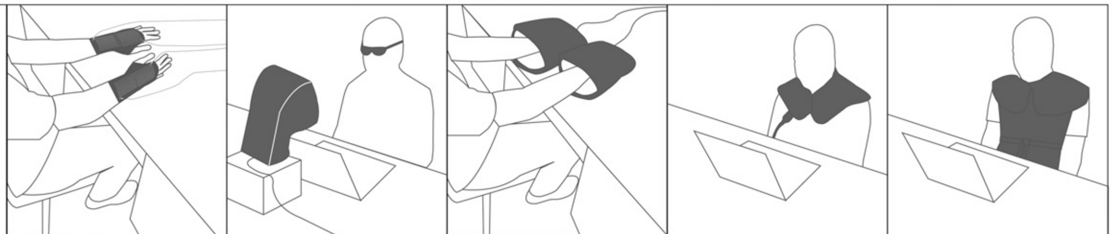
Data Collection and Analysis

Skin temperature was recorded continuously using an Arduino Uno (13 Hz). Thermistors (NTC, 10kΩ, 3% Disc, Vishay BC) were applied using medical adhesives on the stomach and the left fourth fingertip, consistent with Koscheyev et al., 2005. As temperatures were relatively stable in most conditions, a 10-sample moving-average filter was applied for simplicity, and data were rounded to the nearest degree Celsius. Noise was filtered to remove oscillatory temperature change behavior over 1°C between adjacent measurements (Martínez et al., 2016).

During the study, participants rated their perceived thermal sensation and comfort of their whole body and fingers using an adapted ASHRAE scale (Figure 2), at times 5-, 10-, and 15-min (ANSI, 2004; Wang et al., 2007). Upon completion of all test conditions, a focus group session targeted subjects' experiences with the form factors and thermal properties of the devices, to illuminate influences of design and experimental factors (e.g., preferences, form factors, and usability). Participants' feedback was analyzed using affinity mapping strategies, clustering responses to form themes and extract insights.

RESULTS AND DISCUSSION

Here, we discuss influences of thermal dynamics on comfort, as well as user experiences with the thermal devices in lightly controlled field-like environments. We distinguish "direct" and "indirect" forms of heating: for example, Mousepad

	Glove	IR	MousePad	Neck	Torso
Line Drawing of Device					
Product Details	Scuba knit fingerless gloves with two heating elements made with Vectran Liberator 40 conductive thread	Beurer IL50 heat lamp with a 30x40 cm ceramic glass plate and 300 W A15 bulb (ASIN: B001Q3S39K)	Black X heated mousepad hand warmer with padded wristguard, USB powered (ASIN: B07MQPJLC3)	Sunbeam microplush heating neck and shoulders pad, 55 W (ASIN: B001JCXJTW)	ATMOKO multi-purpose shoulder and torso electric fleece heating pads, 220-240 W (ASIN: B07H15BJ69)
Rationale	Heat proximal hands to deliver heat to distal fingertips [Koscheyev et al., 2001]	Heat the face and neck to induce vasodilation in the fingers [Bader & Macht, 1948]	Heat the fingertips (and hands) directly	Heat the vessels in the neck to warm the face and distal fingertips [Koscheyev et al., 2000]	Heat the torso in order to induce vasodilation in the fingers [Bader & Macht, 1948, Brajkovic & Ducharme, 2002]
Measured Device Temperature (°C)	Small: 48 Large: >54*	>54*	30	51	39
Heat Flux (W/m²)	Small: 559.79 Large: 413.65	~2,500	64.75	276.80	176.47

*Temperature exceeded max of sensor range

Figure 1. Readily available heating technologies and their associated parameters.

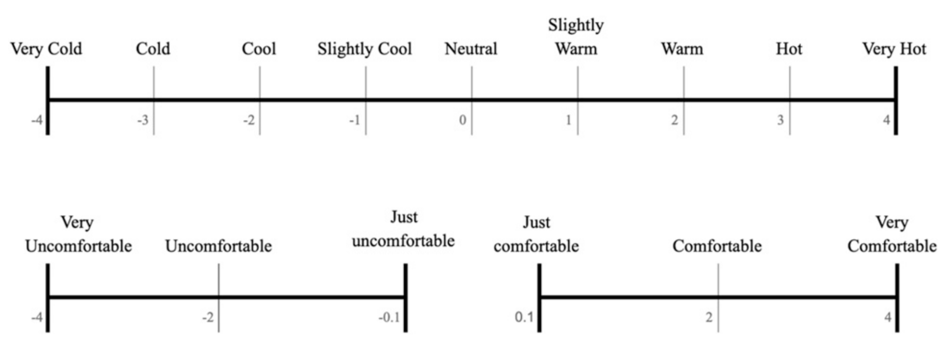


Figure 2. Adapted ASHRAE scale for self-reported thermal sensation and comfort.

directly heats the fingertip sensor, Torso directly heats the stomach sensor, and all other devices are indirect heating.

Study Environmental Condition

Outdoor temperatures during the study ranged from 9–16°C, but indoor environment remained mostly stable at 21°C except for Day2PM (Table 1). Because of morning versus afternoon temperature variation for Day2, we analyzed results in 3 groups: Day1 (P1–P7), Day2AM (P8–P12), and Day2PM (P13–P17).

Measured and Perceived Thermal Stimulus Results

We measured left fingertip and stomach skin temperatures, and subjects' perceived thermal sensations and perceived comfort ratings at the fingers as well as the whole body. We observed temperature stabilization (temperature remaining within 1°C from T10–T15) in 77% (direct) and 63% (indirect) of participants. Interestingly, stabilization was lowest (38%) for participants in the IR condition. To minimize inter-subject variability in interpreting scales and to capture effects of heating stimuli over time, we measured *changes* in skin temperature and self-reported perceived ratings. In Figure 3(a), bars represent average change in measured skin temperature between T15 (trial end) and T0 (trial start). In Figure 3(b), bars represent overall changes in measured perception (top)/comfort (bottom) from T15 (end of trial) to T5.

From Figure 3(a), our results showed that all heating devices generally caused fingertip and stomach temperatures to warm (except for stomach temperature from Neck heating), indicating that all devices were generally successful in warming our subjects. For Day1 and Day2AM, we observed similar (mildly warming) heating effects from the devices without any clear distinction between direct and indirect forms of heating for the two skin temperatures. For Day2PM, we found stronger effects (larger increases in skin temperature) for devices that directly heated the fingertip (MousePad) and stomach (Torso).

It was surprising that direct heating did not always induce large changes at the fingertip. This could be due to other devices having a larger capacity for heat flux and therefore delivering more heat to the whole body. Torso heating had perhaps the most consistent effects, whereby the stomach was warmed the most across all three groups, and the fingertip showed moderate to strong temperature increases. However, the torso heating device covered a large surface area, providing more thermal insulation than other devices. Glove heating (with close proximity to the fingers) yielded only slight increases in fingertip and stomach temperatures. For indirect heating, interestingly Neck heating was more successful in warming the fingertips than Glove heating, but it was ineffective in warming the stomach. By contrast, IR heating was (moderately) effective in warming both the fingertip and stomach.

Table 1. Measured air temperatures during trials

Group	Day	Time	Temperature Range (°C)
Day1	1	AM	21
Day1	1	PM	21
Day2AM	2	AM	21
Day2PM	2	PM	22–24

With respect to *perceived* temperatures, our results showed variability between actual (measured) versus user-reported (perceived) temperature change for all devices. Across the three groups, Neck heating consistently showed poor consistency between actual and perceived effects. Neck heated the fingertips more than the stomach, but the perceived thermal sensation change was relatively small. This may indicate that Neck heating is strongly localized and may distract from thermal sensation change elsewhere. It is hypothesized that for participants with stomach temperatures that lowered with neck heating, neck temperature may be physiologically perceived as core temp, and might induce a decrease to core temperature. Torso heating induced large measured increases in stomach temperature compared to the fingertip, but thermal sensation changes were perceived to be near zero. Yet perceived sensations observed at T15 were high,

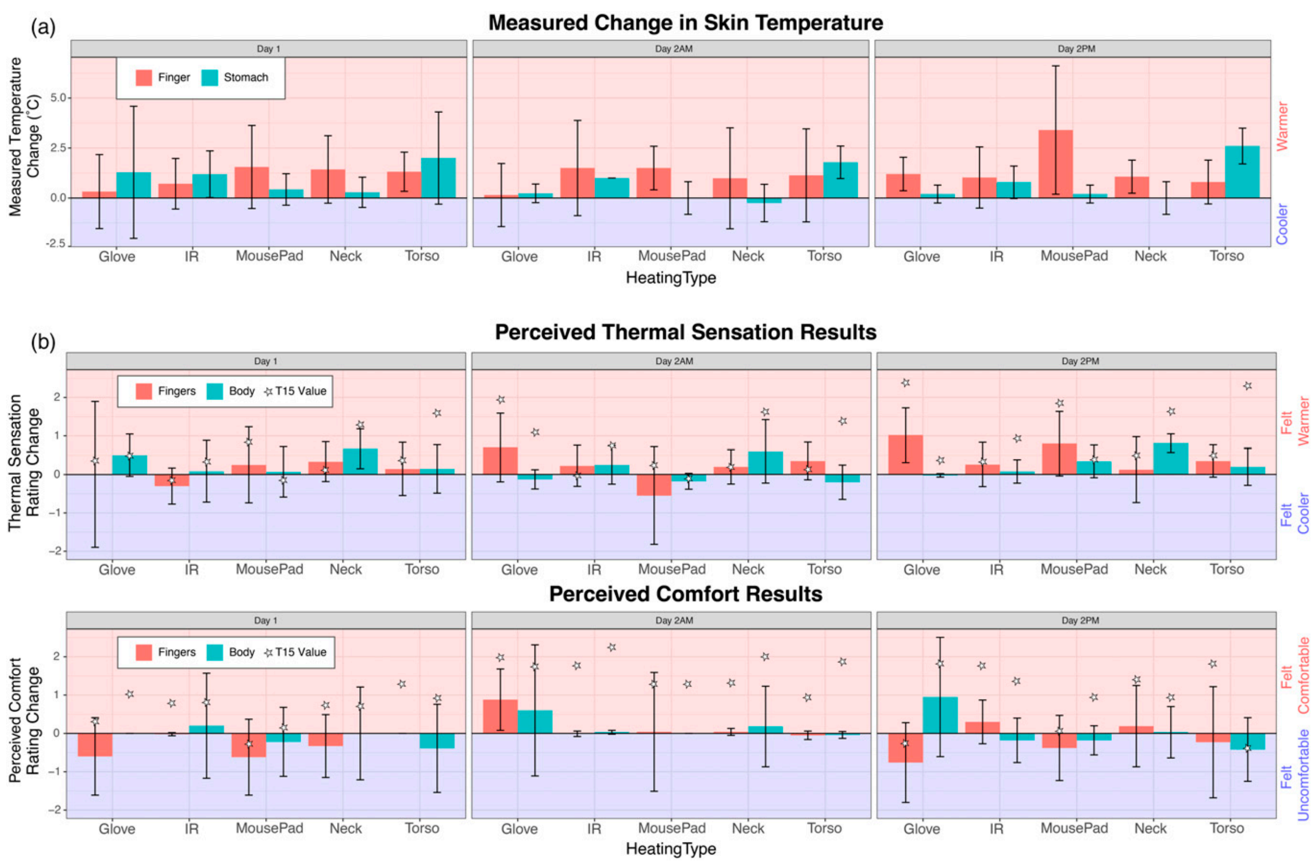


Figure 3. Average change between a) measured skin temperature (T15–T0, mean +/– SD) and b) self-reported ratings of thermal sensation and comfort (T15–T5, mean +/– SD) for each of three study groups: Day1 (n=7), Day2AM (n=5), and Day2PM (n=5).

indicating that users felt warm at both T5 and T15, which could be due to acclimation to the heating device. MousePad had a disproportionately low average perceived thermal sensation rating (fingers) for Day1 and Day2PM. We also observed an inverse relationship between measured temperature and perceived thermal sensation for Day2AM. For Glove heating, temperature changes at the stomach were perceived as thermal sensation changes of the whole body (all groups), but trends were mixed for fingertip temperature and thermal sensation changes. Day1 had extremely variable ratings for thermal sensation changes and on Day2AM users perceived a moderate warming effect that was not measured.

We found discrepancies between measured skin temperature and perceived thermal sensation, consistent with known variability in thermal comfort. Figure 3(b) shows that as the ambient environment becomes warmer, heating can become uncomfortable. The Glove (comfort—fingers), as well as the Mousepad and Torso (comfort—whole body), was perceived as decreasing comfort levels during Day1 and Day2PM, in contrast with near-zero or positive ratings on Day2AM.

However, changes in perceived temperature and/or comfort alone reflect only changes in subjective perception from start to finish; therefore, we also considered T15 averages. We observed slightly cooler ending thermal sensation for IR (fingers) and MousePad (body) during Day1/Day2AM. Overall, the warmest thermal sensations at T15 were Glove (fingers), Neck (body), Torso (body), and Mousepad (fingers). For perceived comfort, Day2AM was unique, with very high average ending comfort ratings for fingers and body observed for all heating types. For Day2PM, the highest T15 thermal sensations were for Glove (fingers) and Torso (Body), but these resulted in the only negative T15 perceived comfort ratings (likely "too warm").

Environmental Effects in Thermal Research

We did not replicate several strong physiological effects seen in controlled studies. The selection of heating strategies in our study was initially motivated by prior work where indirect heating had been effective in warming the fingertips. Unfortunately, the exciting effects seen by Brajkovic & Ducharme (2002) for torso heating were not seen for the device in our study. However, their study was in a very cold chamber (−25°C). Similarly, Koscheyev et al. (2001) saw statistically significant effects on finger temperature from hand and wrist warming, while we saw inverse effects consistent with other studies of this approach (Gagliardi et al., 2018). The Koscheyev et al. (2001) study also took place in colder temperatures, and only included 6 participants. Further, the relationship between fingertip temperature and perceived overall body temperature and comfort as observed by Koscheyev et al. (2001) and others was not consistently replicated in our study. Bader and Macht used an infrared heating device to warm the face in a 23.5°C chamber, producing finger temperature changes of 6.9–8.1° after 80 minutes (3.5–3.6° after 20 minutes). Our participants experienced only 0–2° in a similar time frame.

The difference between our results and prior literature may be explained by environmental differences, participant individual variability, uncontrolled variables (such as metabolism), or other factors. Figure 4 shows high variability (22–35°C) in participants' fingertip temperatures at the very start of the study, consistent with the high variability in blood flow and temperature at the fingertips in the thermoneutral zone (Savage & Brengelmann, 1996; Wang et al., 2007).

Qualitative User Feedback—Focus Group Insights

To gain context about perception and experience, we conducted a focus group. Figure 5 shows total counts for participants' most and least preferred devices. The IR lamp and the Mousepad received entirely negative reviews. IR heating was perceived as uncomfortable and drying to the face/eyes (n=6). The Mousepad was too physically restrictive (n=6), and heat was unevenly distributed across the hand (n=2). The Torso,

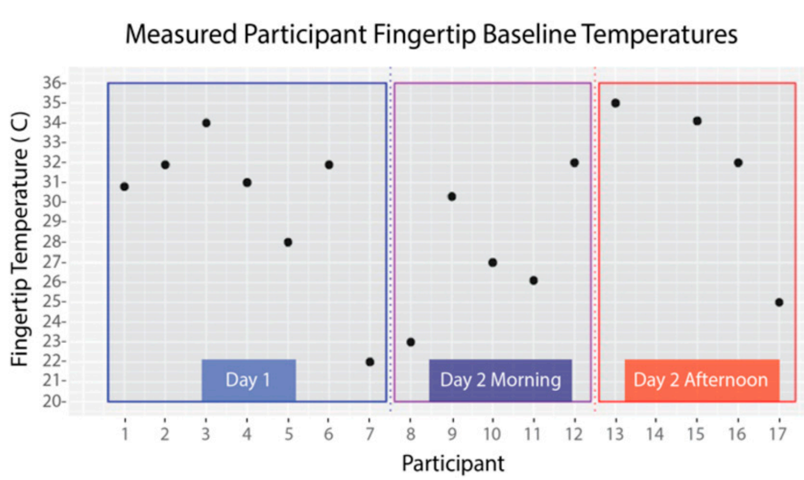


Figure 4. Participant baseline temperature variability.

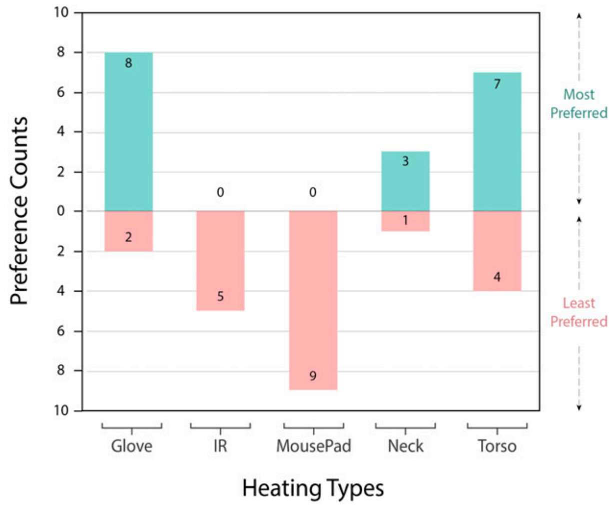


Figure 5. Participant ratings for the most and least preferred heating devices.

Glove, and Neck heating conditions received mixed reviews. In general, participants found the form factor of the Neck device comfortable (*n*=3) and effective at warming (*n*=3) with mostly neutral to slightly positive feedback. In contrast, perceptions of Torso and Glove heating lacked consensus. The Torso device was perceived as too bulky (*n*=8), but also soothing/cozy (*n*=6). The Gloves were ineffective at warming the fingers (*n*=8), consistent with thermal perception results), but the slim form factor was a major benefit (*n*=4).

From the qualitative responses, the major themes observed were (1) usability of heating devices while performing common tasks and (2) the side effects of the heat delivery method. Context influenced opinions: for functional productivity indoors, mobility and practicality factors dominate; for relaxation, form factor dominates. Additionally, negative experiences, unrelated to the efficacy of the heating, were likely to affect perceptions of overall comfort and possibly thermal sensation. However, positive experiences with other aspects of the product could potentially overwhelm the negative experiences with heating. Negative non-thermal experiences can lead to rejection of the device entirely.

Implications and Limitations

This study aimed to investigate variability in physiological and perceptual effects of readily available personal heating devices in thermoneutral environments. Most existing literature on this topic was conducted in more controlled or extreme environments, and/or with limited participant populations, limiting applicability for typical indoor climates and everyday interactive systems.

We found, generally, that readily available heating devices yielded an increase in body and finger temperatures; but the degree of increase varied across heating conditions. While previous studies suggested finger or peripheral temperature as the strongest correlate of overall thermal sensation, our results did not always support that. Further, we found contradictions in participants' measured body temperature and perceived experience as well as comfort preferences. There may be differences between perceptions of skin temperatures affected by externally applied heat stimuli, and those affected by changes to blood flow. Perhaps the most significant takeaway was the degree of observed variability between participants both in physiological response and subjective experience when using on-body thermal augmentation in typical indoor climate–controlled environments.

It is clear that the translation of mechanisms that have been measured in laboratory conditions to a quasi-field environment may not be as direct as expected. The results presented offer a broad approach to characterizing some of the variability in thermal experience and physiology as it might be experienced in a field environment. The following summary reflects the insights derived from this investigation:

1. In this context, body surface temperatures did not reliably reflect perceived thermal comfort or expressed preferences. Hence, it is unlikely that specific body temperatures alone will be effective control inputs.
2. Given that thermal comfort is a complex, individual physio-cognitive process, customizability of the system is needed to allow adaptation of the location(s) and magnitude of temperature change.
3. It is likely that the relationship between surface temperatures and preferences will need to be learned for each individual and may need to continue to adapt to external contextual factors like environment and activity.
4. Device form factor has a dominating influence on perceived thermal sensation and comfort and should be carefully considered for different use contexts.

The insights drawn from this study lead to recommending torso and glove-based wearable systems for person heating devices (among the devices tested), but the focus group data and fingertip baseline temperatures uncovered the importance of a multi-layered human factors approach for product development in this space. Wearability and end-user experiences should be well understood alongside functional quantitative data.

Importantly, this study is inherently limited. In contrast to a laboratory study, the variability between participants, the tasks they undertook, and in the ambient environment certainly influenced the experiences recorded. There were also important differences between heating devices. The devices tested varied in terms of participant exposure location, heating area, and heat flux, which may have caused differences in localized and overall body temperatures. Future work includes further researching the interactions between thermal sensation, thermal comfort, and overall comfort in larger sample sizes to validate this study's insights for heating devices used in indoor environments.

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Ellen Dupler *is a human factors and systems engineer, specializing in the wearable device development and usability testing. Her latest research has included wearable stretch sensor characterization and development, investigations on wearable thermal systems, and collaborative digital projects. Her current work focuses on wearable device design and about integrated connected health user experiences. She is currently based in Minneapolis, Minnesota.*

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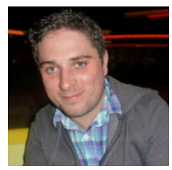

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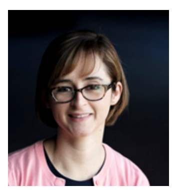

Lucy E. Dunne *is currently a Professor at the University of Minnesota, where she directs the Apparel Design program and co-directs the Wearable Technology Lab. She holds degrees in Apparel Design (BS, MA, Cornell University), Electronic Technology (AAS, Tompkins-Cortland Community College), and Computer Science (PhD, University College Dublin). Her research focuses on textile- and garment-based wearable technologies, human factors of wearable systems, and manufacturing and use of next-generation clothing.*

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