Title

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Evaluating the Comfort of Thermally Dynamic Wearable Devices

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Abstract

Thermal discomfort is a widespread problem in the built environment, due in part to the variability of individual occupants' thermal preferences. Personal comfort systems (PCS) address this individual variability, and also enable more energy-efficient thermal conditioning in buildings by reducing the need for tight indoor temperature control. This study evaluates a novel approach to PCS that leverages the time-dependence of human thermal perception. A 6.25 cm^2 wearable device, Embr Wave, delivers dynamic waveforms of cooling or warming to the inner wrist. In three thermal comfort tests conducted in a climate chamber with N = 49 subjects and temperatures between 20 and 28 ºC, the device exhibited a corrective potential of 2.5 ºC within 3 minutes for both warm and cool populations, while consuming ~1 W of power. The effect is even more pronounced (corrective potential up to 3.3 ºC over periods of 3- and 45-minutes) when subjects are given control of the device's operation. Subjects are found to optimize the device settings for pleasantness, not for the intensity of sensation. These results indicate that this low-power, wearable device improves whole-body thermal sensation, comfort, and pleasantness. It is an appropriate tool for addressing the problem of thermal discomfort in moderate indoor environments.

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Keywords: thermal comfort; wearable comfort device; personal comfort system; alliesthesia; waveforms; thermal pleasantness

1. Introduction

1.1. Thermal comfort in the built environment

Thermal discomfort consistently ranks among the top complaints in the built environment [1,2]. Solutions are urgently needed, because indoor thermal discomfort negatively influences occupant stress levels [3], work productivity [4], and indirectly the building's energy consumption [5,6].

One of the primary challenges in indoor thermal comfort is that occupants' thermal sensation and thermal preferences within a given environment vary widely from individual to individual. Perceiving a room as warm versus cool, or comfortable versus uncomfortable, is an individual experience. In addition to environmental factors like the temperature, it depends on personal factors such as clothing level, activity level, previous thermal exposure [7] and even the mental state of the individual [8]. The one-size-fits-all approach of central heating, ventilation, and air conditioning (HVAC) in buildings has been fundamentally unable to satisfy more than about 80% of their occupants because of these large individual differences. Individual variability in thermal sensation, comfort, and acceptability under controlled conditions is typically 0.8~1.2 Likert scale units on 7-point scales, roughly equivalent to 2~3^{o}C in room temperature [9].

1.2. Wearable comfort devices

Personal comfort systems (PCS) are devices that cool or heat occupants individually [10]. Various forms of PCS have been studied in laboratory and field studies, including ceiling fans, radiant or convective heaters, and temperature-controlled surfaces on chairs, desks, and floors. By giving occupants control over their own thermal status – and therefore correcting their perceived temperature towards what is comfortable for them – these systems and devices are designed to address the problem of individual thermal variability. They work because warming and cooling stimuli on local parts of the body have the ability to affect the entire body's thermal sensation [11,12,13]. Our whole-body cold- or hot-uncomfortable complaints are often dominated by cold or hot extremities [14], and PCS can directly improve overall comfort by delivering local warming or cooling to these extremities. PCS devices can also sometimes benefit from the alliesthesia they induce in people, a sensation of overall pleasantness that occurs as physiological thermal stressors are locally relieved [11,15,16]. Currently, PCS are typically furniture-scale devices, but they can also be designed at a smaller wearable scale so that they follow the occupant throughout the day. Making PCS both wearable and thermally effective poses challenges in terms of the device's size, location, weight, and daily operating (battery) life.

To date, very few wearable comfort devices have been manufactured and evaluated. A number of prototypes of such devices have been reported in the research, development, and demonstration (RD&D) phases. Erwin [17] listed 18 wearable or portable comfort-control products that existed as of 2017. We tabulate their related literature with some recent additions in Table 1. There are 8 in the clothing fabric or footwear category, 3 in the jewelry category (the Apple Watch which communicates with thermostats, a neck collar with heating and cooling functions, and the Embr Wave wristband being studied here), 2 personal comfort systems (the heated/cooled chair and footwarmer developed by some of the authors of this paper [18,19,20] and 4 portable air conditioning units. Among these, only 5 are available on the market, one of them being Embr Wave. In addition to the devices listed in Table 1, Lopez et al. [21] tested a warming-only wearable prototype that applied both static and cycling temperature patterns on different locations of the wrist (outer side of wrist, outer-and-inner-sides together, left-and-right-sides together). They found that the cyclic heating rhythms are more efficient than continuous heating for whole body thermal sensation and the wrist warming can improve thermal sensation of fingertips. Another wearable

PCS is a head-neck cooling device developed by Wang et al. [22], but it is designed for sports injury treatment and not for providing comfort in a normal building environment.

Table 1: Summary of wearable comfort devices (based on the Table 1 in reference [18])

Type	Project/Product title	Description	Status
Clothing	Adaptive Textiles Technology (ATTACH) []	Smart garments that enable building occupants to adjust their personal temperature settings and promote thermal comfort to reduce building-level air conditioning.	RD&D
	Kuchofuku ACC []	Jacket with ventilation cooling function	In market
	Meta-cooling textile []	Clothing made from textile that can dynamically gate infrared radiation.	RD&D
	Passive Thermal Adaptive Textile []	Thermally adaptive textile that change in thickness in response to temperature change.	RD&D
	Photonic Structure Textiles []	Integrate photonic into textiles to achieve heating or cooling	RD&D
	Wearable Electroactive Textile []	Wearable Electroactive Textile for Physiology-based Thermoregulation	RD&D
	ThermoComfort Cloth []	Dynamically adjustable thermoregulatory fabric.	RD&D
	ThermoRegulatory Clothing System []	Ventilated clothing that enables expansion of comfortable temp range	RD&D
Furniture-scale PCS	Advanced Personal Comfort Systems [9, 19,21]	Optimize the efficiency and demonstrate practical applicability of personal comfort systems in offices.	RD&D
Furniture-scale air conditioner	Electro Active Smart Air-Conditioner Vent Registers (ESAVER) []	Air conditioning vent capable of modulating airflow distribution, velocity and temperature around occupants.	RD&D
	Evapolar portable air conditioner []	Desktop air conditioner that chills, humidifies, and purifies air	In market
	Micro-environmental control system []	Near range microenvironmental control system.	RD&D

	Robotic Personal Conditioning Device []	Cooling robot that follows a person.	RD&D
Jewelry	Apple Watch []	Watch with internet connection to thermostats or other air conditioning devices. But no heating/ cooling function by itself.	In market
	Wearable, neck-hugging device []	Portable air conditioning with	In market
	Embr Wave Bracelet []	A wrist band that heat or cool building occupants to improve comfort and save energy.	In market

The Embr Wave, developed by Embr Labs, is to the authors' knowledge the first commercially available jewelry-style wearable comfort device with heating and cooling functions. The device delivers warming or cooling in rhythms tuned to human temperature perception, with the user controlling the wave amplitude to suit their preferences. The time-dependence of human thermal perception increases the effect of this stimulus on comfort. The heating and cooling cycling also minimizes the device battery power requirements and facilitates waste heat rejection. Although the existence of Embr Wave has been mentioned in the literature before, this paper is the first full-scale study of this technology's effects on human thermal comfort and sensation.

1.3. Objective

Using human subjects in controlled conditions, we test the hypothesis that the Embr Wave wearable device, localized to a single body location and consuming ~1 W, meaningfully affects whole-body thermal perception in both warming and cooling modes.

2. Materials and methods

2.1. Device

The Embr Wave wrist band is worn on the inside of the wrist and delivers cooling or warming in the form of dynamic waveforms. The device is powered by a Li-ion battery, and utilizes a thermoelectric (Peltier) heat pump to modulate temperature against the wearer's skin. The thermoelectric element is thermally bonded to a natural convection heat sink with a cooling/heating area of 6.25 cm^2. A light bar indicates heat/cooling status and also serves as slider for user interface. The red side indicates warming and the blue cooling. Figure 1 shows the device schematic.

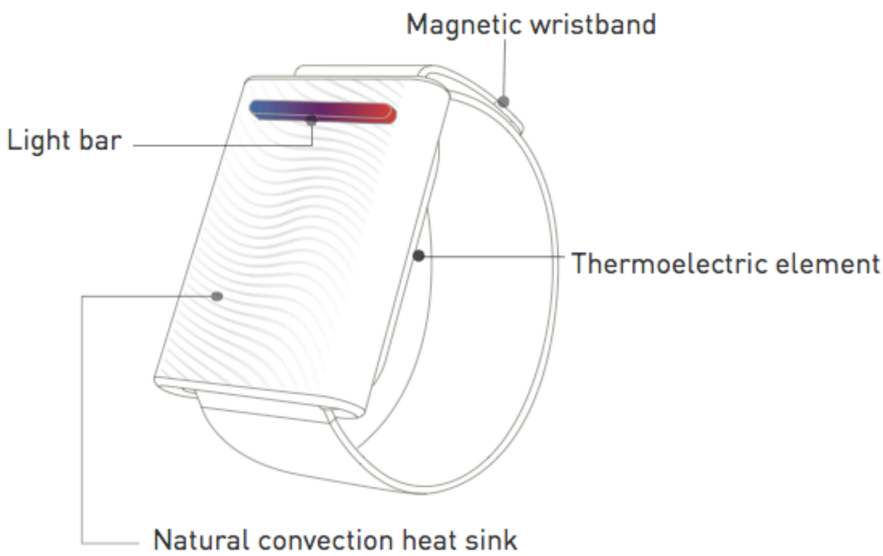

Figure 1: Embr Wave wrist band device

A microcontroller operates a closed-loop temperature control system, taking temperature inputs with <0.1 ºC resolution from two thermistors that are bonded to the heatsink and the skin side of the thermoelectric element respectively. The output from a proportional integral derivative (PID) control system drives the thermoelectric element to produce waves of heating or cooling on the skin (or 'waveforms') that are designed to maximize thermal sensation per unit energy.

2.2. *Thermal waveforms*

Embr Labs has developed thermal waveforms [23] designed to generate strong periodic thermal sensations based on the neurophysiological properties of warm and cool thermoreceptors. This waveform structure takes advantage of the known sensitivity of warm and cool thermoreceptors to rapid changes in temperature [24]. The periodic waves minimize the time-averaged power consumption to 1 W.

Figure 2 shows the default warming and cooling waveforms. The oscillating temperature profiles are centered around the median temperature levels of 36.5ºC for warming and 28.5ºC for cooling. During the personalized operation and extended use pilot (See 2.3), subjects are allowed to control the median temperature within the outer ranges of 32-42ºC for warming and 25-30 ºC for cooling. These ranges are based on the known thermal sensitivity of warm and cool thermoreceptors in the skin. In particular, warmth thermoreceptors have a maximal signal firing rate around 44 ºC, and cold receptors around 25 ºC [25,26,27]. The Embr Wave device limits the upper temperature below the maximal sensitivity, however, because 44 ºC is close to the heat pain threshold [39,40]. The warming waveform has an amplitude of 0.7ºC and cooling waveform has an amplitude of 1.0ºC, values derived from empirical tests of perceived pleasantness.

The rates of change in the waveform profiles are fixed for both warming and cooling, at 0.4 and 0.6 ºC/s, respectively. These rates of temperature change were chosen because they are sufficiently high to trigger an "overshoot" effect, in which the thermoreceptor firing rate spikes in response to a sufficiently rapid temperature change [12,41]. By reducing the fraction of the time that the system is on, these temperature profiles reduce the natural acclimation to localized sensation that occurs under static contact heating or cooling [28]. They also reduce the power required by the thermoelectric element.

Since its commercialization in March 2018, the Embr Wave device has gained new functionalities that were not available at the time of the study described in this paper. During this study, the duration of operation of the device was limited to 3 minutes for cooling waveforms and 5 minutes to warming waveforms. To facilitate comparisons, we set the testing time to 3 minutes for both warming and cooling in the test protocol. Extended duration technology was completed after this study will be the subject of a future investigation.

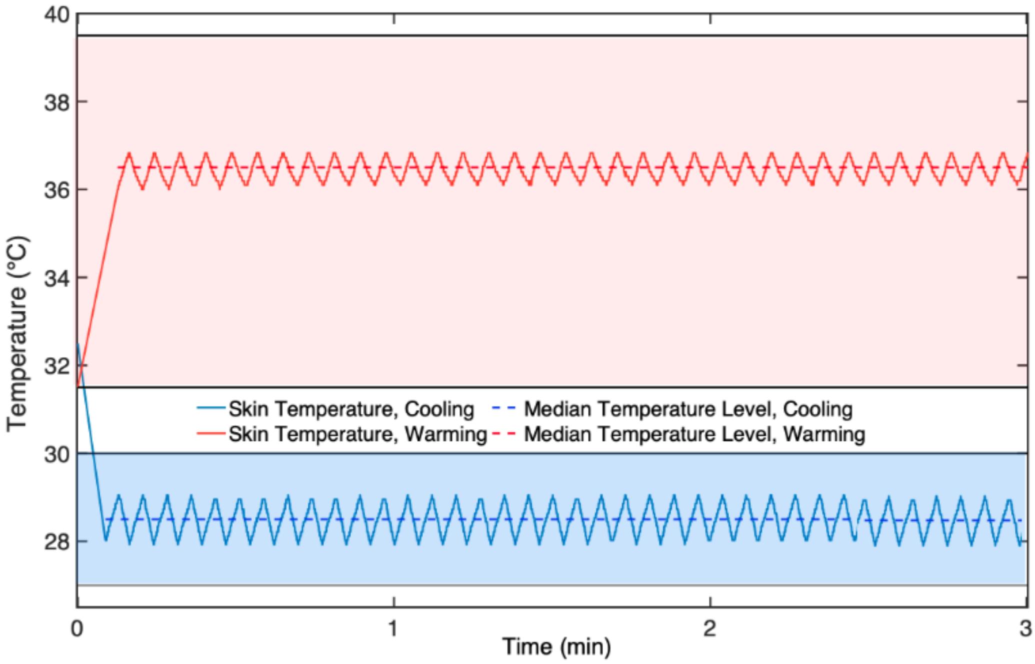

Figure 2: The median temperature levels (dashed) and oscillating skin temperatures (solid) over time, as used for warming and cooling in Exercise 1 described below. The range of all possible temperature levels for warming and cooling are shown by the shaded areas of the figure.

2.3. Human subject test design

Test conditions and participants

The testing was done in two steps with different subjects: a pilot test and a main study. The pilot test took place in November 2017, and involved 23 college-age subjects in three different cool- to slightly-warm ambient temperatures: 20º, 23º, and 26°C on different days. The subjects first used prescribed levels of the heating and cooling functions of the Embr Wave wrist band over three-minute periods. Then over a prolonged session (45 min), subjects freely used the heating and cooling functions based on their personal preferences, and performed multiple evaluations. The pilot test was intended to evaluate the overall effectiveness of the wrist band at heating and cooling people at different ambient temperatures and identify the range of ambient temperatures under which the wristband is effective. It also served to observe how subjects use the device over a prolonged period.

The results of the pilot study were published in a previous paper [29]. Warming cool people (people who voted <-0.5 on the Whole Body Thermal Sensation scale), and cooling warm people (people who voted >0.5 on the Whole Body Thermal Sensation scale), the wrist band created average whole-body sensation changes of 0.76 scale units for warming and 1 unit for cooling. Whole-body comfort increased 0.86 for warming and 0.98 unit for cooling, on a 7-unit comfort scale.

Based on the pilot results, we designed the experimental plan for the main study. It was evident from the pilot that its warm condition at 26°C room temperature had not induced a high enough percentage of the population to report discomfort. Accordingly, we chose temperatures of 20 and 28°C in the main study to provide roughly comparable comfort improvements on the warming and cooling sides.

The main study took place in February 2018. 49 college-aged subjects (26 females, 23 males) participated in the one-hour-long test at the 20°C condition. Following this test, 47 of these subjects (24 females and 23 males) within two weeks participated in the 28°C test (two females dropped after the first test due to class schedule conflicts). All testing was completed within a month. In both the 20º and the 28ºC tests, the subjects used the Embr Wave at fixed heating and cooling levels over three-minute sessions. This was followed by a "free adjustment" three-minute session in which subjects could freely use heating or cooling functions to suit their individual preference. The test protocol is described below (Figure 3). This paper will focus on the results from the main study, but will also report on results from the prolonged (45 minute-duration) personalized-use session from the pilot study.

The chamber relative humidity was controlled around 40%, representing a typical value for air-conditioned buildings. The underfloor air supply system was used to maintain the air speed in the occupied zone below 0.2 m/s. Uniform clothing was provided in all the test conditions. Subjects wore a cotton long-sleeve button down shirt, cotton long pants covering ankles, and normal shoes with socks. The estimated clothing insulation is between 0.7 and 0.8 clo.

Test protocol

The experimental protocol for the main study is presented in Figure 3 below. Each test started with a 45-minute acclimation period and the first thermal comfort voting. Following this, while wearing the device on their left wrist, subjects completed three sessions that each ended with thermal comfort and sensation voting.

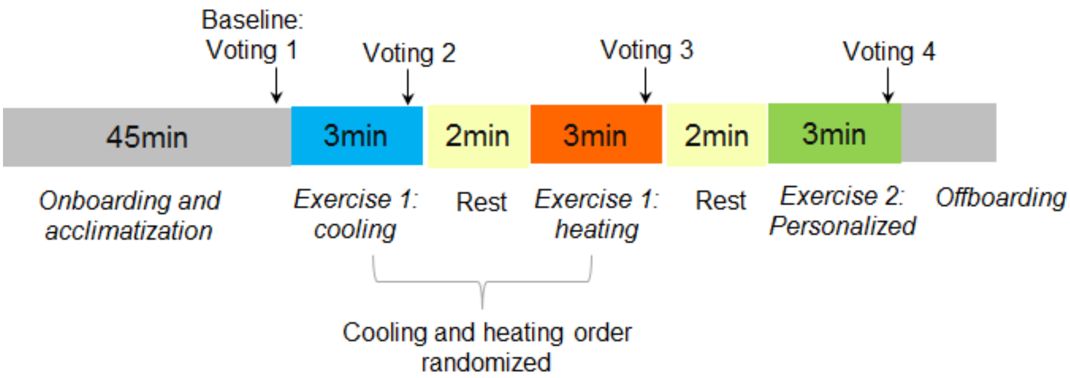

Figure 3: Test protocol for each test in the main study. Subjects performed three tests on different days in different environmental conditions.

Baseline. In the 45 min acclimation period, subjects entered the test chamber, exposing them to the thermal conditions of the day's test. During the acclimation period, no personal comfort devices were provided. Close to the end of the acclimation period, participants answered a questionnaire designed to evaluate their thermal sensation and thermal preference. This survey (voting 1 in Figure 3) serves as the baseline of the experiment. The questionnaire is described in further detail in Table 2.

Exercise 1: Fixed warming or cooling. Participants were provided with Embr Wave devices programmed to deliver 3 minutes of a fixed warming waveform followed by 3 minutes of a fixed cooling waveform, or vice-versa. The order of the heating and cooling in Exercise 1 was randomized for each subject, and the waveforms were separated by 2 minutes of rest in all cases. In the last 45 seconds of each 3-minute exposure, participants answered the comfort questionnaire during a voting session.

Exercise 2: Personalized warming or cooling. For the next 3 minutes, participants were allowed to adjust the device's median temperature level as they saw fit. The allowed levels included both warming and cooling, with temperatures ranging from 25ºC to 40ºC, and input with a step size of 0.75ºC (warming) and 0.5ºC (cooling). In total, there were 7 levels available for both warming and cooling. As in Exercise 1, participants answered the comfort questionnaire during the last 45 seconds of the 3-minute exposure.

Exercise 3: Warming or cooling over an extended period of time. This exercise is taken from the pilot study, in whose final session the participants were allowed to control the device as they saw fit for 45 minutes. During this period, the devices were programmed to turn off after 3 minutes of continuous operation in cooling mode and after 5 minutes of operation in warming mode, thereby requiring the participant to repeatedly turn it back on in order to continue receiving warmth or coolth. This protocol was due to a technical limitation of the device at the time of testing, but it created an opportunity to gauge user engagement by requiring them to continue to activate the device to experience the desired effects. Participants answered the comfort questionnaire before this exercise began, and then completed the same comfort questionnaire five times over the course of the 45-minute session at fixed timestamps (t = 5, 15, 25, 35, and 43 minutes).

Subjective questionnaire

The questionnaires were designed to evaluate both the participants' local and whole-body thermal sensation, comfort, and pleasantness. The questions asked during each exercise are listed in Table 2. Participants were asked to answer each question on a continuous Likert scale. For data analysis, the thermal responses on the Likert scale were converted to numerical values, where the distance between any two Likert steps equals 1 and the steps are equally divided, to a resolution of 0.1.

Table 2: Sensation reporting questions

Metric	Options
Whole-body Thermal Sensation	Very Hot (+4), Hot (+3), Warm (+2), Slightly warm (+1), Neutral (0), Slightly cool (-1), Cool (-2), Cold (-3), Very Cold (-4) (note: the middle 7 Likert categories are identical to those of the ASHRAE 7-point thermal sensation scale)
Whole-body Thermal Comfort	Very comfortable (+3), Comfortable (+2), Just comfortable (+1), Just Uncomfortable (-1), Uncomfortable (-2), or Very Uncomfortable (-3)
Whole-body Thermal Pleasantness	Very pleasant (+3), Pleasant (+2), Slightly pleasant (+1), Indifferent (0), Slightly unpleasant (-1), Unpleasant (-2), or Very unpleasant (-3)
Whole-body Thermal Preference	Prefer cooler, Prefer no change, or Prefer warmer
Left Wrist Thermal Sensation	Very Hot (+4), Hot (+3), Warm (+2), Slightly warm (+1), Neutral (0), Slightly cool (-1), Cool (-2), Cold (-3), Very Cold (-4)
Left Wrist Thermal Pleasantness	Very pleasant (+3), Pleasant (+2), Slightly pleasant (+1), Indifferent (0), Slightly unpleasant (-1), Unpleasant (-2), or Very unpleasant (-3)

2.4. Theory and analysis

Corrective power

In order to quantify the effect of the device on comfort, we also calculated its Corrective Power (CP) for each exercise. CP quantifies the ability of a PCS to shift occupants' thermal sensations toward neutral in any given non-neutral thermal environment. CP is often converted into an effective temperature difference, which represents the system's ability to "correct" the ambient temperature toward the thermally neutral temperature. In this form, CP is the difference between two ambient temperatures at which equal thermal sensation is achieved - one with no PCS (the reference condition), and one with the PCS in use [10]. Temperature CP was calculated as:

$$CP = \left(WBTS_{exercise} - WBTS_{baseline}\right)/G \quad (\text{ºC})$$

where $WBTS_{exercise}$ is the whole-body thermal sensation reported at the end of the warming/cooling exercise, $WBTS_{baseline}$ is the whole-body thermal sensation reported in the baseline period, and G is a temperature conversion coefficient. It has been shown that $1/G$ is variable, with values ranging from 2 to 6 ºC per Likert scale unit depending on the nature of the occupancy, with lower numbers for more highly controlled environments [10,30,31] and for PCS devices that affect smaller areas of the body [10,32]. In this study, we chose a middle value of 3.0 ºC per scale unit (G=0.33 sensation unit/°C). This value also matches the temperature dimensions of the ASHRAE and ISO comfort zones, which span one scale-unit from 'slightly cool' to 'slightly warm', and which can be seen to be 3 ºC wide over an extended range of ambient conditions [33].

Subject grouping

At the same ambient temperature, some participants are expected to perceive the room to be cooler than neutral, some to perceive it warmer than neutral, and the remainder to perceive it as neutral [8,**Error! Bookmark not defined.**]. Because the purpose of a PCS is to improve individual thermal comfort, and because the participants' needs for warming and cooling will differ at any given condition, we evaluated the effect of the Embr Wave wrist band for two subpopulations of interest based on their answers to the baseline sensation questionnaire:

- Subjects who perceived the thermal environment as cooler than neutral (Whole-body Thermal Sensation < "Slightly Cool" or below) *and* preferred the environment to be warmer (Thermal Preference = “Prefer Warmer”) are referred to as the **cool population**.

- Subjects who perceived the thermal environment as warmer than neutral (Whole-body Thermal Sensation = “Slightly warm” or above) *and* preferred the environment to be cooler (Thermal Preference = “Prefer Cooler”) are referred to as the **warm population**.

A small number of subjects who did not meet either criteria were excluded by the definitions. For the remainder of this paper, we focus the data analysis on evaluating the effects of the device in cooling for the warm population, and in warming for the cool population.

Data analysis

The thermal sensation, comfort, and pleasantness reported during each exercise were compared with the baseline values obtained for each session in order to evaluate the change in local and whole-body sensations that resulted from the device. Each participant’s baseline answers were compared with their answers from each exercise using a 2-tailed t-test to evaluate statistical significance. The following criteria were used for statistical significance. All the data analysis and statistical tests were performed in R 3.5.1.

- * indicates p-value between 0.01 and 0.05, which is significant;
- ** indicates p-value between 0.001 and 0.01, which is very significant
- *** indicates p-value below 0.001, which is highly significant

3. Results

3.1. Baseline whole-body thermal sensations and preferences

The baseline questionnaire results show that at the two different ambient temperatures (20 ºC and 28 ºC), there is variability in both whole-body thermal sensation and thermal preference across the population of participants. The large standard deviations (1.1 Likert scale units for the 20 ºC condition and 0.8 Likert scale units for the 28 ºC condition) and wide spreads in the first-third quantile (1.3 Likert scale units for the 20 ºC condition and 1.0 Likert scale for the 28 ºC condition) confirm that there is marked intra-individual difference in thermal sensation.

Figure 4 is a Sankay diagram that shows the relationship between baseline environmental temperature, whole-body thermal sensation, and thermal preference among subjects at baseline before using the device. It shows subjects' voting flows using the band widths as proportional indicators. At the same ambient temperature, subjects might have a different whole-body thermal sensation; and at the same whole-body thermal sensation, subjects might have different thermal preferences. In 20ºC, 80% of subjects felt 'slightly cool' to 'cold' while 20% of subjects voted neutral or slightly warm.

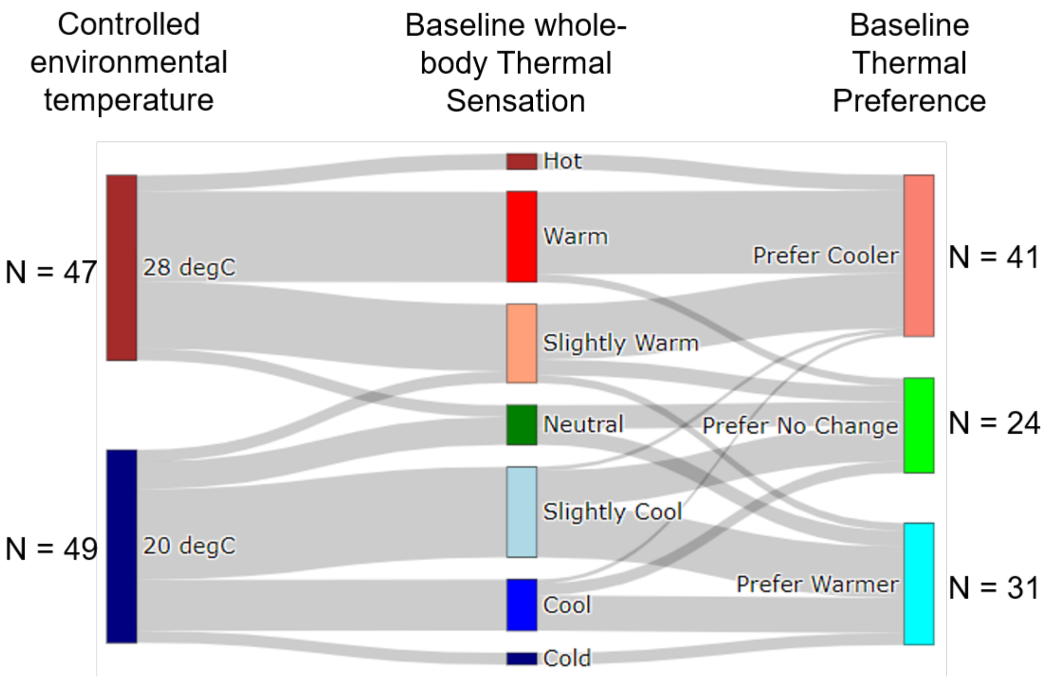

Figure 4: Relationships between controlled environmental temperature, and subjects' baseline whole-body thermal sensations and thermal preferences, prior to using Embr Wave

The sizes of the 'warm' and 'cool' populations defined in Section 2.4 were N = 39 and N = 25 respectively.

3.2. Whole-body thermal sensation, comfort and pleasantness with the Embr Wave wrist band

Table 3 shows the whole-body thermal response of the cool and warm populations to the use of the wrist band during difference exercises. With fixed stimulus levels, warming the cool population (2nd column in the table, bold) or cooling the warm population (5th column, bold), changed the whole-body sensation around 0.85 Likert scale units from the baseline value towards neutral.

Under both warming and cooling, whole-body comfort and pleasantness were enhanced by 0.5 to 1.0 Likert scale units. Fixed cooling of the cool population (1st column) and warming the warm population (4th column) did not produce significant negative impacts. The personalized adjustment exercises (3rd and 6th columns, bold) gave each participant freedom to tailor their heating and cooling stimuli, and the improvements are for most measures slightly better than for the fixed cooling and heating stimuli. In general, the wristband produced stronger effects when cooling the warm population than when warming the cool population.

Table 3: Change in reported values in cool and warm populations after using Embr Wave, relative to baseline.

	Cool population (TS < -0.5 & TP = warmer, n = 25)			**Warm population** (TS > 0.5 & TP = cooler, n = 39)		
	Cooling Exercise	**Warming Exercise**	**Free Adjustment Exercise**	Warming Exercise	**Cooling Exercise**	**Free Adjustment Exercise**
Whole-body Sensation	0.32	**0.86****	**0.86*****	-0.29*	**-0.82*****	**-1.09*****
Whole-body Comfort	0.15	**0.53**	**0.73**	0.27	**0.95*****	**1.00*****
Whole-body Pleasantness	0.11	**0.50**	**0.56**	-0.11	**0.64***	**0.61***

3.3. *Left wrist sensation and pleasantness*

In order to see how these changes to the whole-body perception were associated with the effect of the wrist band, we present the local thermal sensation and local pleasantness measurements for the left wrist in Figure 5 and Table 4. Figure 5 shows that the warm population went from experiencing a 'slightly warm' and 'slightly pleasant' wrist sensation at baseline without the wristband (grey diamond), to experiencing a 'cool' and 'slightly pleasant' sensation during fixed cooling (first red diamond), and finally arriving at a thermal sensation that was weaker but even more pleasant when they were allowed to personalize the temperature (upmost red diamond). Similarly, the cool population went from feeling 'slightly cool' and 'indifferent' at baseline (grey square), to experiencing 'warm' and 'pleasant' sensations during fixed warming, and finally arriving at a thermal sensation that was less strong but even more pleasant during the user-controlled phase (blue squares). Note that the reverse operation (cooling the cool population and warming the warm population) both increases the starting sensations in cooler or warmer directions and lowers their pleasantness votes from 'indifferent' to 'slightly unpleasant'.

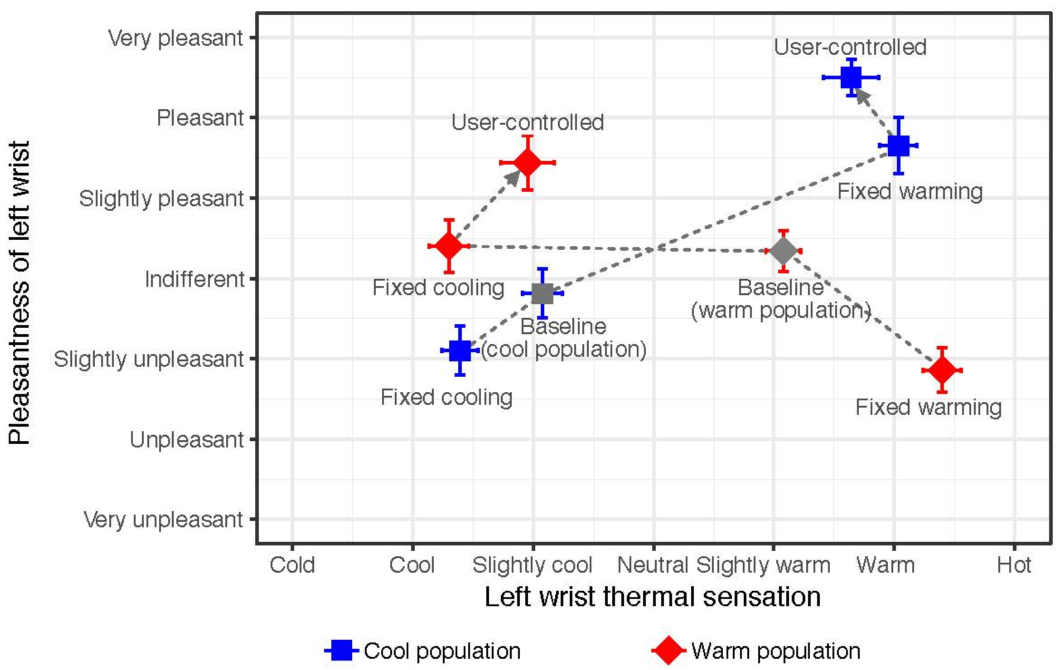

Figure 5: Local thermal sensation and local pleasantness at baseline (grey diamond for warm population, and grey square for cool population), and after 3 minutes of fixed cooling, fixed warming, or user-controlled operation. Error bars denote standard error.

Table 4 provides the magnitudes of the changes to local sensation and pleasantness that are presented in Figure 4. The fixed warming/cooling for cool or warm populations created about 3 sensation unit changes to the left wrist, with these changes reduced to about 2.5 units under user-control. Pleasantness is enhanced an additional 1 pleasantness unit under user-control, over that of fixed warming/cooling.

Table 4 also presents the median temperatures for the fixed warming and cooling, and the user-controlled warming and cooling. Compared to the medians for fixed stimuli, subjects under user-control chose on average 1 °C lower median temperature in warming and 0.6 °C higher in cooling. The changes they made to the fixed stimuli may explain the final sensation differences seen in Figure 4.

The small pleasantness seen in fixed cooling the warm population may have resulted from an overly-strong cooling stimulus in the fixed cooling exercise, which occupants subsequently reduced during the personalized exercise. Our chosen fixed cooling stimulus was too strong to maximize pleasantness, much more so than our warm stimulus.

Table 4: Left wrist thermal response of cool and warm populations after using Embr Wave, relative to baseline.

	Cool population (TS < -0.5 & TP = warmer, n = 25)			**Warm population** (TS > 0.5 & TP = cooler, n = 39)		
	Cooling	Warming	Free Adjustment	Warming	Cooling	Free Adjustment
Left-wrist Sensation	-0.68**	**2.96*** **	**2.57*** **	1.32***	**-2.78*** **	**-2.13*** **

Left-wrist Pleasantness	-0.71	**1.84*** **	**2.69*** **	-1.48***	**0.06**	**1.10***
Median Temperature (± Standard Deviation)	28.5°C	**36.5°C**	**35.5 (±2.6) °C**	36.5°C	**28.5°C**	**29.1 (±0.8) °C**

Comparing local sensation and pleasantness results with those of the whole-body, we see that the magnitude of local sensation and pleasantness changes exceed the whole-body changes by 2 – 3 times. It is interesting to see that participants reported a slightly *stronger* improvement in whole-body thermal sensation in the user-controlled phase, even as the local sensation on their wrist felt *less* intense.

3.4. Whole-body Corrective Power (CP)

Figure 6 shows the CP associated with fixed warming and fixed cooling (Exercise 1), as well as with personalized warming and personalized cooling (Exercise 2) for both the cool population and the warm population. The data were obtained by converting the whole-body thermal sensation changes (Table 3) to the CP using the method described in section 2.4.

For both warm and cool populations, the device had a CP of 2.5 ºC for fixed cooling ($p < 0.001$) and for fixed warming ($p < 0.001$). The figure indicates no statistically significant effect from warming the warm population, or cooling the cool population.

When participants were allowed to control the temperature level as they saw fit (Exercise 2), the average CP for the warm population increased by 33%, from 2.5 ºC to 3.3 ºC. This is also probably due to the fixed cooling stimulus which was too strong to be optimal. For the cool population, giving participants control over the warming level did not increase the CP compared with the fixed level from Exercise 1.

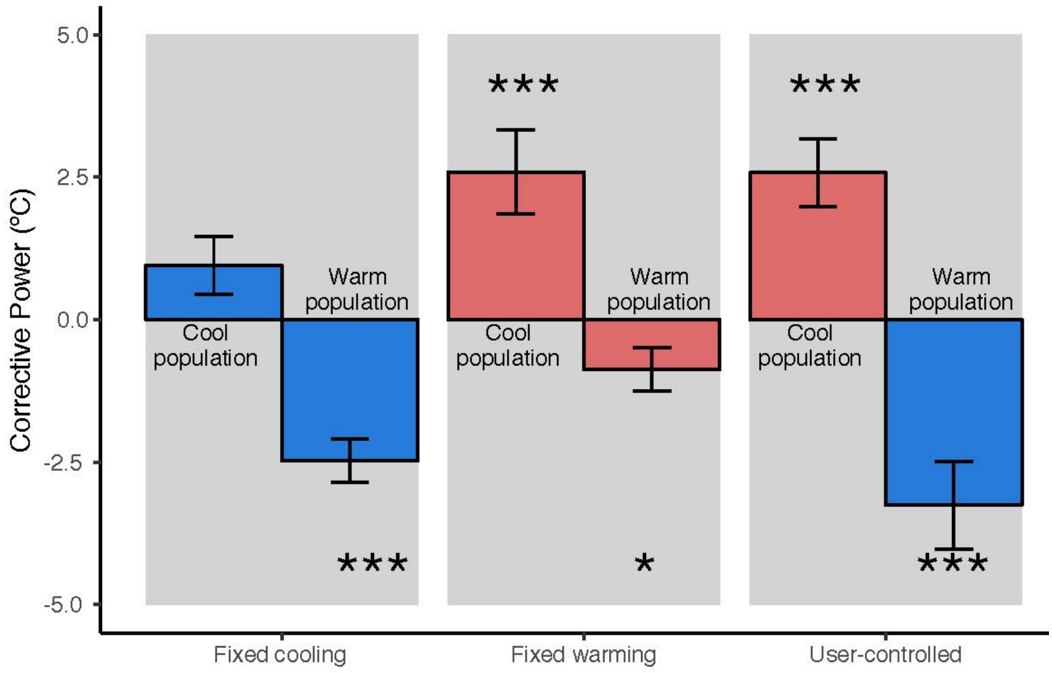

Figure 6: Whole-body CP of Embr Wave after 3 minutes of fixed cooling, fixed warming, or user-controlled operation, shown for both the warm population and the cool population. Error bars denote standard error.

3.5. Gender comparison

Gender differences are compared in Table 5**Error! Reference source not found.**. Of the 39 participants in the warm population, 19 were male and 20 females. Of the 25 participants in the cool population, there were far fewer males (9) than females (16). The men felt less cool than females, and thus selected themselves out of the cool population.

With Embr Wave, the whole-body sensation and comfort improvements are larger for women than for men. This difference is especially pronounced for the session in which the cool population is warmed, with the magnitudes 2-3 times larger for women than men. The lack of statistical significance in the male portion of the cool population is probably due to their small number.

Table 5: Thermal response of cool and warm populations after using Embr Wave, relative to baseline.

		Warm population (TS > 0.5 & TP = cooler, n = 39)		**Cool population** (TS < -0.5 & TP = warmer, n = 25)	
		Cooling Exercise	Free Adjustment Exercise	Warming Exercise	Free Adjustment Exercise
Whole-body sensation	Male	-0.65***	-0.47**	0.33	0.45
	Female	-0.99***	-1.67**	1.17**	1.09***
Whole-body comfort	Male	1.1**	0.94**	-0.56	-0.39
	Female	0.81*	1.06*	1.15**	1.36**

3.6. Utilization over a prolonged period

Figure 7 shows the utilization of the device over the 45-minute period in the pilot study. The figure indicates that the cool population (Figure 6a) chose to exclusively use the device in warming mode. No members of this group chose to use cooling at any time. Over 45 minutes, the average utilization rate of warming in the cool population was 76%. The cool population reported an average change in whole-body thermal sensation of 3°C ($p < 0.001$) compared to the baseline established just before the utilization exercise. This CP is similar to the CP observed in the main study during 3 minutes of user-controlled operation 3.3°C. However, the figure also indicates a gradual decrease in the reported CP over the 45 minutes. This will be addressed in the discussion section below.

Although most of the warm population used the device in cooling mode, one warm subject chose to use the device in warming mode during parts of this exercise (as shown by the red bars on the top of the cool population figure). Over 45 minutes, the average utilization rate of cooling by the warm population was 44%. The warm population reported an average change in whole-body thermal sensation of -2.4 °C (p

< 0.001), which is also similar to the value during 3 minutes of user-controlled operation (CP=2.4 °C). Unlike the cool population, the warm population exhibited a gradual increase in the reported CP over the 45 minutes, although the utilization rate decreased after the first 10 minutes. The measured CP for the warm population in this exercise is less significant and more variable than for the cool population, possibly related to the smaller population size and lower utilization rates of cooling (addressed in the discussion section below). Nonetheless, across the 45-minute utilization exercise, the warm population still reported a statistically significant improvement in thermal comfort (+0.6 scale units, $p < 0.001$).

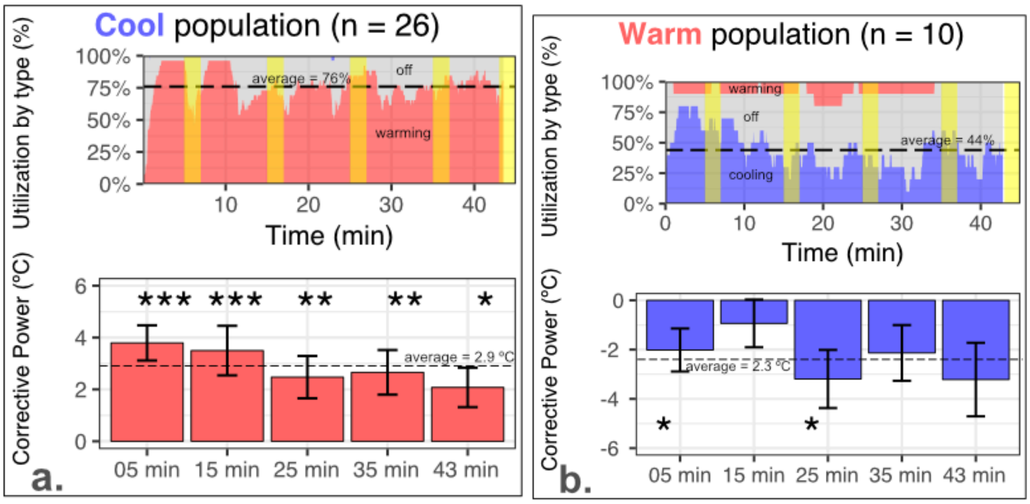

Figure 7: Utilization of the device over 45 minutes and corresponding whole-body CP for both (a) cool and (b) warm populations. Yellow bands indicate times when participants were asked to answer sensation questions.

4. Discussion

4.1. Baseline variability

The subjects' baseline variability (Figure 5) indicates that in any given room temperature, the study participants experienced widely different whole-body thermal sensation. The standard deviation of reported whole-body thermal sensation under identical environmental conditions was in the range of 0.8 – 1.1 Likert scale unit, and its first-third quantile ranged from 1.0 to 1.3 scale units. This range is consistent with other recent studies of individual variability in whole-body thermal sensation, which found that individual difference in thermal sensation is around 1 Likert scale unit [9] under a wide range of environmental conditions.

4.2. Significance of corrective power measured in this study

In both fixed and user-controlled sessions, the device has a statistically significant whole-body CP on the order of 2~3 ºC for both the warm population and the cool population, and for both the 3-minute (Figure 6) and 45-minute (Figure 6) session lengths. In other words, the device made the cool population more comfortable as if the room had been 2-3 ºC warmer, and similarly for the warm population as if the room had been 2-3 ºC cooler. This is a significant finding, since it only takes a few degrees to make most building occupants more comfortable.

4.3. Reasons for the device effectiveness

We attribute the strong effect of the device to several factors. First, the dynamic temperature profiles leverage the human body's natural sensitivity to rates of temperature change, and these profiles operate entirely within the temperature ranges that maximize thermoreceptor firing rates, as described in Section 2.2. Second, the device's location –the inner wrist – is a relatively temperature-sensitive area of the body. Finally, recent comfort modeling [13] shows that the single strongest local body-segment sensation contributes 90% of the correction of whole-body sensation, the second strongest local sensation contributes only 10%, and the remaining weaker stimuli do not contribute. The stronger sensations monopolize the person's attention. In the corrective direction (warming the cool population or cooling the warming population), the device is producing the single strongest local sensation on the wearer's body, and although the area is small, it can still contribute significantly to the

correction of whole-body sensation. This latter phenomenon might underlie much of the 2~3 ºC CP, and the improvement to the wearer's overall comfort.
These local sensations are improving overall thermal comfort without greatly changing the heat balance of the body. This effect applies only in correcting discomfort under moderate conditions in which there is no risk of hypo- or hyperthermia. The local sensations generated by the device are not strong enough to overcome discomfort from severe thermoregulatory stress.

4.4. Cooling versus warming

The stronger cooling CP on the warm population than the warming CP on the cool population may result directly from the characteristics of warm and cool thermoreception. Cold-sensory spots on the skin greatly outnumber warm-sensory spots [40,34,35], and their neurophysiological properties differ. Cold thermoreceptors have significantly higher conduction velocities than warm receptors [36,37]. Cold receptors are also located within or immediately beneath the epidermis at an average depth of 0.1 to 0.15 mm, while the warmth receptors are deeper at an average depth of 0.3 to 0.6 mm [42]. In an analogous test, Filingeri et al. [43] tested thermal perception responses to a 14 mm diameter thermal stimulus applied to subjects' palms. Cold stimuli were perceived much more quickly than warm stimuli of equivalent intensity. Together, the results from this paper's Embr Wave tests are consistent with our understanding of thermoreception in the skin.

4.5. Sensation and pleasantness

The hypothesis that alliesthesia is contributing to the observed trends is supported by the results of the user-controlled operation exercise. In operating the device, both warm and cool populations naturally chose stimulus temperatures and sensation intensities that maximized pleasantness – not the intensity of the local sensation (uppermost points on Figure 5, and Table 4). This behavior may seem intuitive – that an uncomfortable person would optimize for what feels best, not what feels most intense – but its implications should not be overlooked. In particular, participants reported a slightly *stronger* improvement in whole-body thermal sensation in the user-controlled phase, even as the local sensation on their wrist felt *less* intense. This may be consistent with previous findings that small, personally-induced changes in thermal conditions can significantly improve comfort [38,39].

4.6. Operation and utilization over prolonged periods

The results in Figure 6 illustrate that localized warming or cooling continues to have a statistically significant effect on thermal comfort over a prolonged period of 45 minutes, although the magnitude of the effect decreases over time. This suggests there may be limits to the amount of time that a PCS such as the Embr Wave can be continuously used to address thermal discomfort. At the same time, it also highlights an opportunity for thermal waveforms that are better optimized for prolonged usage. The thermal waveforms that were used in this study had been specifically designed to provide an optimal 3-minute session, and further work by the authors since the study was performed suggests that a more intermittent rhythm of waves helps prevent the decline in CP over a period of 30-minutes. Although we observed ~1^{o}C CP drop after 45 minutes device usage, the CP for periods of 3-minute to 15-minute length is still valuable for comfort in real buildings, in which many thermal discomfort problems are transient issues with the building and with movement among its occupants.

The 45-minute sessions also showed that utilization was higher for the cool population using warming (76%) than for the warm population using cooling (44%). We attribute this effect primarily to the configuration and limitations of the device. The device was programmed to warm for 5-minute intervals but only cool for 3-minute intervals, so maintaining cooling required more engagement from the wearer than warming. Furthermore, the device's ability to cool in its current implementation was limited by its ability to dissipate heat into the environment, which naturally worsens in warm environments. Subjects, at times, had to wait additional minutes for the device to recover before being allowed to continue cooling. Nonetheless, it is noteworthy that the warm population was able to experience a meaningful CP over a prolonged 45-minute period while only activating the device 44% of the time. This suggests that thermal comfort does not necessarily require nonstop warming or cooling: having access to short interventions (3-5 minutes) on an as-needed basis seems to help participants improve their thermal comfort over a prolonged period.

4.7. Limitations

This study focused primarily on studying short-term effects using trials that lasted only 3 minutes, and explored their use over 45 minutes in a smaller pilot study. Improved heating and cooling waveforms that operate over extended periods were not yet available and will need to be investigated. The results from this study show that the efficacy of Embr device is measurable and applicable to relieving discomfort caused by temperature transients in the built environment, but do not address the effectiveness of the device over many hours or a full work day.

In the next phase of the project, we will perform studies of comfort effects of the wristband over longer periods with extended and intermittent thermal waveforms. Field studies will be employed to validate comfort effects of the wristband in real world, with a larger range of age groups, where user adoption and behavioral thermoregulation may become larger factors.

5. Conclusions

This study shows that a wearable device delivering dynamic thermal waveforms to the skin of the wrist can statistically improve whole-body thermal sensation, comfort, and pleasantness about 0.5 - 1 scale unit, which is equivalent to about 2-3 ºC ambient temperature difference in periods ranging from 3 to 45 minutes of use. The impact on the left wrist is about 2 – 3 times stronger than the impact on the whole body. When subjects are given control of the device's operation, they tailor the device settings to optimize for pleasantness, not for the intensity of sensation. The device's corrective power is larger for women than for men, and it is somewhat larger for cooling warm populations than for warming cool ones.

Thermal variability among occupants is the primary cause of the widespread thermal discomfort in buildings, and is an intractable problem for conventional heating and cooling control. The novel wearable comfort device evaluated in this paper shows significant promise for addressing thermal discomfort caused by individual variability. The individual variability in thermal perception – as measured by the standard deviation in whole-body thermal sensation – is ~1 step on a 7-point Likert scale, and the device shows an average effect of ~1 step on this same Likert scale. In this sense, the device is an appropriate tool for addressing the problem of thermal discomfort in moderate indoor environments.

By moving from the whole body and static heat fluxes (conventional thermal comfort) to continuous, localized warming and cooling (workstation personal comfort systems), to dynamic and localized sensations, wearable personal comfort systems can become "available anytime" technology. At scale, the adoption of a PCS with a CP of 2-3 ºC could have a transformative impact on energy consumption and productivity in the built environment, by reducing the demands caused by occupant complaints on central HVAC systems, and by reducing productivity losses tied to currently unmitigated thermal discomfort.

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