The Effect of a Low-Energy Wearable Thermal Device on Human Comfort

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SUMMARY

This paper explores the ability of a low-energy wearable thermal device to improve whole body thermal comfort. The wearable device is a wristwatch-like thermal device with a 25mm * 25mm contact heating and cooling surface. Twenty-three subjects were recruited for testing in a climate chamber, with each participating in three 2-hour tests. The three tests were at 20, 23, and 26ºC ambient conditions. It was found that the local warming and cooling had a significant effect for subjects who felt cool or warm before using the device. The wearable device was able to improve whole-body thermal sensation about 1 scale unit towards neutral. The whole body thermal comfort was also improved significantly by the wearable device if subjects felt discomfort before using it. For people who felt neutral prior to use, the improvement of using the wearable device was small but also statistically significant. The concept of localized, individually-controlled thermal wearable devices is promising in providing energy efficient thermal comfort, especially considering the wide interpersonal differences in thermal comfort, and the device's low energy consumption. [174 words]

KEYWORDS
Thermal wearable device, Personal Comfort System (PCS), Local Contact Heating and Cooling, Corrective Power

1 INTRODUCTION

Over the past decade, thermal comfort understanding has been evolving beyond static, isothermal conditions to those that are dynamic and non-uniform. This trend is clearly reflected in the recent increasingly thorough studies of Personal Comfort Systems (PCS).

1.1 Uniform comfort zone vs. Individual difference

Unlike traditional air-conditioning systems aiming to create a uniform 'neutral' thermal environment, PCS emphasizes personal control to meet diversified individual demands. Building occupants have large interpersonal comfort differences. Analysing about 16,762 sets of field study data from ASHRAE database I, Humphreys and Nicol (2002) demonstrated large interpersonal differences in thermal sensation and satisfaction. Under the same conditions (environmental, clothing, and metabolic), the standard deviation of people's thermal sensation is 1.2 scale, which corresponds to 3.6K ambient temperature difference (http://comfort.cbe.berkeley.edu/). Because of such large differences, it is not possible to create an environment that satisfies every individual (Nakano et al. 2002). The occupant satisfaction rate measured in buildings is considerably lower than the target value of 80% given in ASHRAE Standard (Huizenga et al., 2006; Karmann et al., 2017), regardless of the enormous amount of energy consumed to create the uniform 'neutral' environment. PCS addresses these differences by providing an increment of local heating or cooling that is directly under the occupant's control. Bauman et al. (1998)'s field study in a bank office showed that with PCS, occupants' satisfaction reached 100%.

Zhang et al. (2015) proposed the concept of Corrective Power (CP) to quantify the ability of PCS to correct the thermal non-neutral state of subjects. CP is defined as the difference between two ambient temperatures at which the same thermal sensation is achieved – one with PCS in use, and one without PCS (uniform environment with subject voting neutral) as the reference condition. Zhang et al. (2015) found that the CP of cooling PCSs ranges from 1-6 K, and the CP of heating PCSs ranges from 2-10 K. Many of the PCS devices are able to correct the 3.6K interpersonal differences presented by Humphreys and Nicol.

The CP of PCS can not only satisfy thermal comfort requirements but also reduce the energy use and carbon emissions from heating and cooling the building, since with PCS it is no longer necessary to control the indoor temperature within a narrow range. Relaxing the temperature range markedly reduces building HVAC energy consumption and its associated carbon emission (Hoyt et al, 2015).

1.2 Static neutral vs. thermal alliesthesia

In addition to the correction of non-neutral thermal states, PCS provides the opportunity of thermal alliesthesia. Arens et al. (2006) observed that thermal neutral conditions were perceived as 'comfortable' but not 'very comfortable'. The 'very comfortable' votes were perceived only when some level of thermal stress/discomfort is being removed. The higher levels of thermal comfort or pleasure are known as thermal alliesthesia. Zhang et al. (2003, 2010) developed thermal sensation and comfort models counting the alliesthesia, and provided a spatial allisthesia definition in Zhang et al. (2015).

de Dear and Parkinson have published a series of papers to introduce and prove the conceptual framework of thermal alliesthesia (de Dear 2011; Parkinson & de Dear 2015, 2016, 2017; Parkinson et al. 2017). Positive alliesthesia is pleasantly perceived if the local cooling or heating is able to offset or counter a thermoregulatory load-error. Parkinson & de Dear (2016) specifically studied contact heating on the ball of the foot and on the palm of the hand as a source of alliesthesia through laboratory approaches. They found that applying local warming had a significant increase ($p<0.05$) on whole-body thermal sensation for people who felt cool before the local heating application, but not significantly increase on thermal pleasure. Only a minority of participants experienced strong and sustained pleasure in response to localized heating. Parkinson & de Dear (2016) concluded that the success of local contact heating heavily depends on some form of individual control.

1.3 Research goal

Wearable thermal devices are now technologically feasible because of the advances currently enabling the Internet of Things (Smith et al., 2017). Like PCS, wearable devices provide personally controlled local warming and cooling of one or more body segments. Unlike most PCS, wearable devices warm and cool only a small area within a body segment. Whether they are effective for heating or cooling has not been tested. Spatial summation is a well-known phenomenon in thermal sensitivity (Stevens *et al.*, 1974), so it is possible that the areas influenced by wearable devices might be too small to be effective.

The aim of this study is to explore the effect of a wearable thermal device on whole body thermal comfort. The key question to be answered is: whether the wearable device is able to correct perceived thermal non-neutrality, and how effective the wearable device is to correct the whole-body sensation towards neutral and to improve the comfort level. To answer this question, a chamber experiment was designed, which will be described in Section 2. Experimental results will be presented in Section 3, and the discussion and conclusion in Section 4.

2 METHODS

2.1 Participants, chamber and apparatus

Twenty-three subjects (17 females, 6 males), aged between 18 and 30, participated in the study. The clothing was standardized during the experiment with the total clothing insulation level of 0.65 clo (0.58 clo from clothing + 0.07 clo from chair): long-sleeve shirt, long trousers, underwear, socks and shoes, and a chair, which is a mech chair with reflective surfaces in the back and bottom seat.

The experiment was conducted in the climate-controlled environmental chamber at the University of California, Berkeley in December 2017. Three chamber temperatures were set to create different thermal sensation: 20ºC (PMV = -1.34), 23ºC (PMV = -0.44), and 26ºC (PMV = 0.45), with the temperature variation controlled within 0.5ºC. The chamber was conditioned by underfloor air supply.

The Embr Wave (Figure 1(a)), an energy-efficienct wristband that uses a battery-powered thermoelectric module, was used in this study to deliver local heating and cooling. As shown in Figure 1(b), the wristband is supposed to be located on the inner side of the wrist with an effective heating/cooling area of 25mm * 25mm. Three levels of dynamic heating and cooling were delivered by the Embr Wave during this study. The exact temperature profiles are not reported here, but levels for this study were selected based on achieving a desired range of subjective sensations. The maximum heating and cooling power of the Embr Wave Wristbands is 2W.

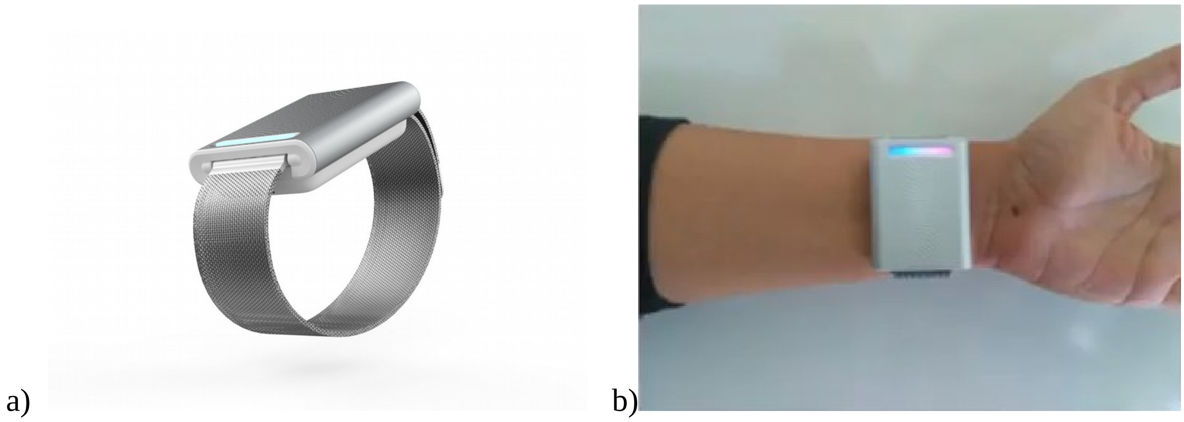


Figure 1. Apparatus to deliver local heating and cooling: a) Embr Wave wristband, b) Embr Wave worn on the wrist. (images courtesy of Embr Labs)

2.2 Procedure

Subjects were required to participate in three experiments with different ambient temperatures as described above. Each experiment involved three phases prior to offboarding, as depicted in Figure 2. In the acclimation phase (reference condition), subjects were seated in the chamber for 45 minutes without the wristband. At the end of this phase, subjects were invited to vote on the thermal environment. The sensation exercises (phase II) started after voting on the reference condition. Three levels of heating and three levels of cooling were provided. To avoid the influence of previous thermal exposure, there was a one-minute break before entering the next level of heating/cooling, and a two-minute break when switching from warming to cooling conditions. The detailed procedure of how the three heating and cooling were delivered is shown in the bottom of the Figure 2. The sensation exercise took about 20-30 minutes. After the sensation exercise, subjects moved to the personal use exercise (phase III), during which subjects were allowed to freely utilize the wristband to improve their thermal comfort. The usages were recorded during the 45 minute test. This paper is a preliminary analysis of the effect of the wristband, and focuses only on the reference and sensation exercise portions of the experiment.

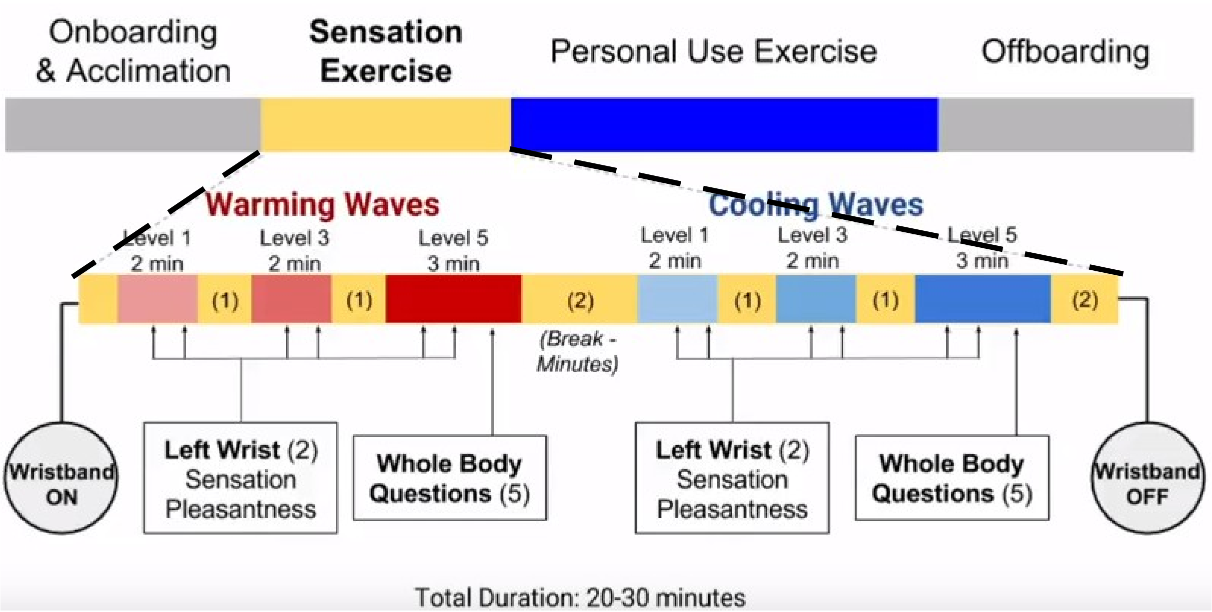


Figure 2. Experiment procedure

Five types of thermal subjective evaluation questions were asked during the experiment: four with continuous scales: thermal sensation (9 points), thermal comfort (7 points), thermal pleasantness (7 points), thermal acceptability (5 points); and one with a discrete scale: thermal preference (3 points). The whole-body thermal sensation and thermal comfort scales are illustrated in Figure 3. Both wrist- and whole-body questions were asked during the experiment.

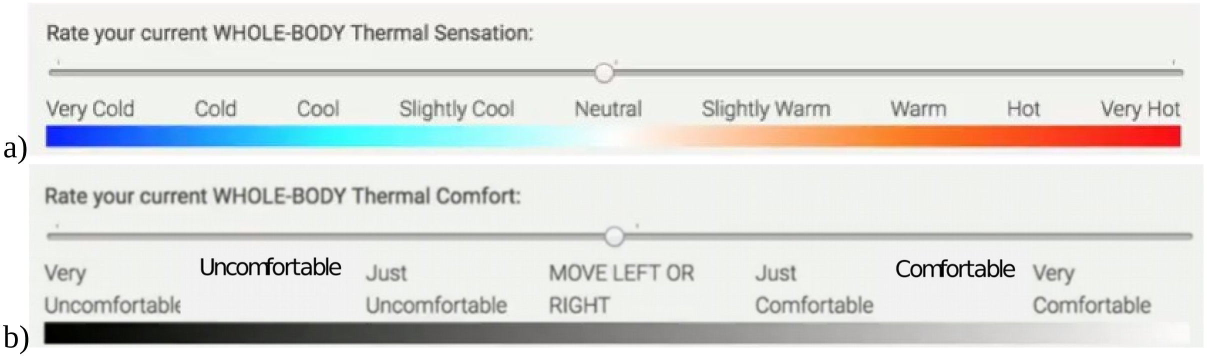


Figure 3. Survey scale a): thermal sensation 9-points scale, b) thermal comfort 7-points scale

A paired 2-tail T-test was utilized to examine whether the wristband was able to significantly improve thermal comfort levels. In the analysis, * indicates $p < 0.05$, ** indicates $p < 0.01$, *** indicates $p < 0.001$.

3 RESULTS

3.1 Individual difference

Figure 4 illustrates the thermal sensation and preference votes at the end of the acclimation phase, which serve as the reference votes. The top figure shows that under each of the three ambient temperature conditions, people's sensations are spread more than 5 different places along the sensation scale. Under 20°C and 23°C ambient conditions, there were people on both warm and cool sides. These results indicate individual differences. The individual difference could be further observed from the lower figure that at 23°C and 26°C, about half of the subjects wanted no change and about half wanted to be warmer or cooler. These results indicate that some form of PCS is needed to satisfy such diversified demands.

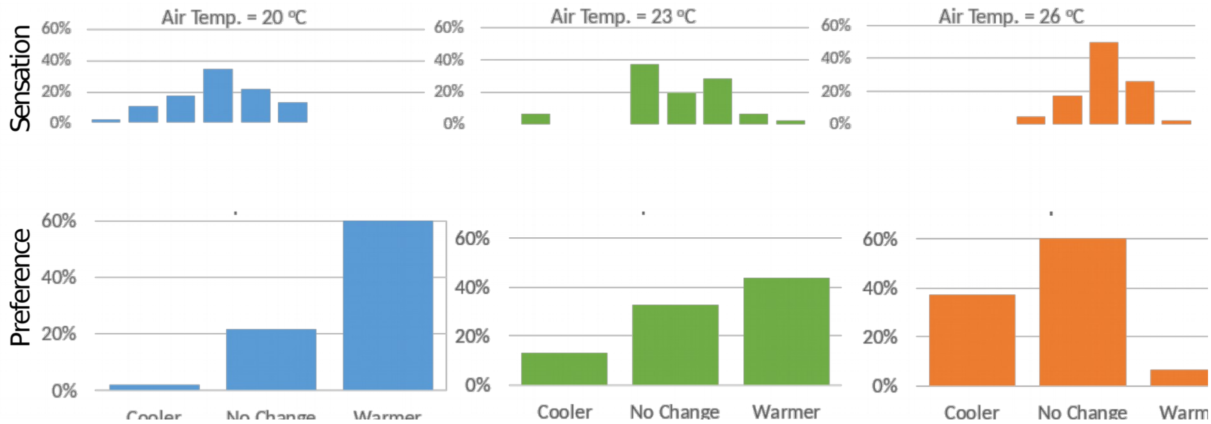
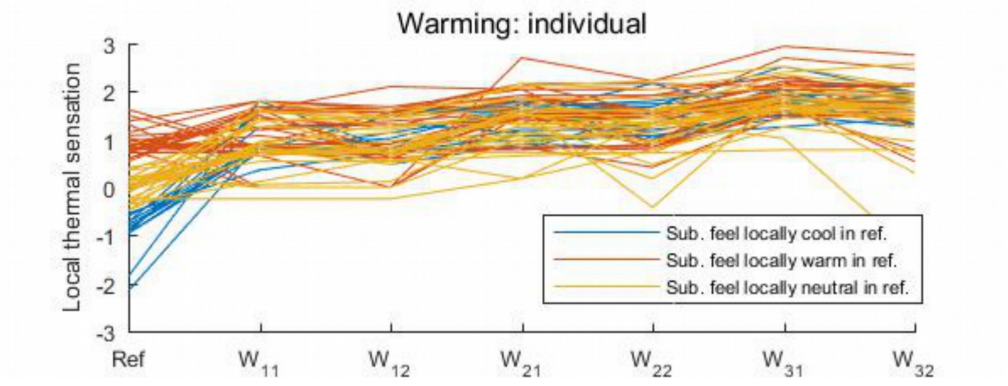


Figure 4. Thermal sensation and preference votes during the reference condition

Figure 5 tracks the local thermal votes of individual subjects under imposed localized warming and cooling. Subjects are clustered based on their local thermal sensation vote without the wearable devices (locally cool: vote below -0.5, neutral: vote between -0.5 and 0.5, warm: vote above 0.5). Subjects experienced three levels of warming/cooling, and voted their local sensation and pleasantness twice for each local thermal stimulus, at an interval of 45 seconds.

Two observations can be drawn from the parallel plots. First, the local thermal sensation vote is more consistent, with a narrower range, than the local pleasantness vote, indicating that individual difference in local pleasantness is larger than in local sensation. This is understandable since thermal pleasantness involves more subjective judgement than thermal sensation. Second, the individual perception of local thermal stimuli varies significantly between subjects even when they have similar reference thermal perception and are exposed to the same thermal stimuli.



(a)

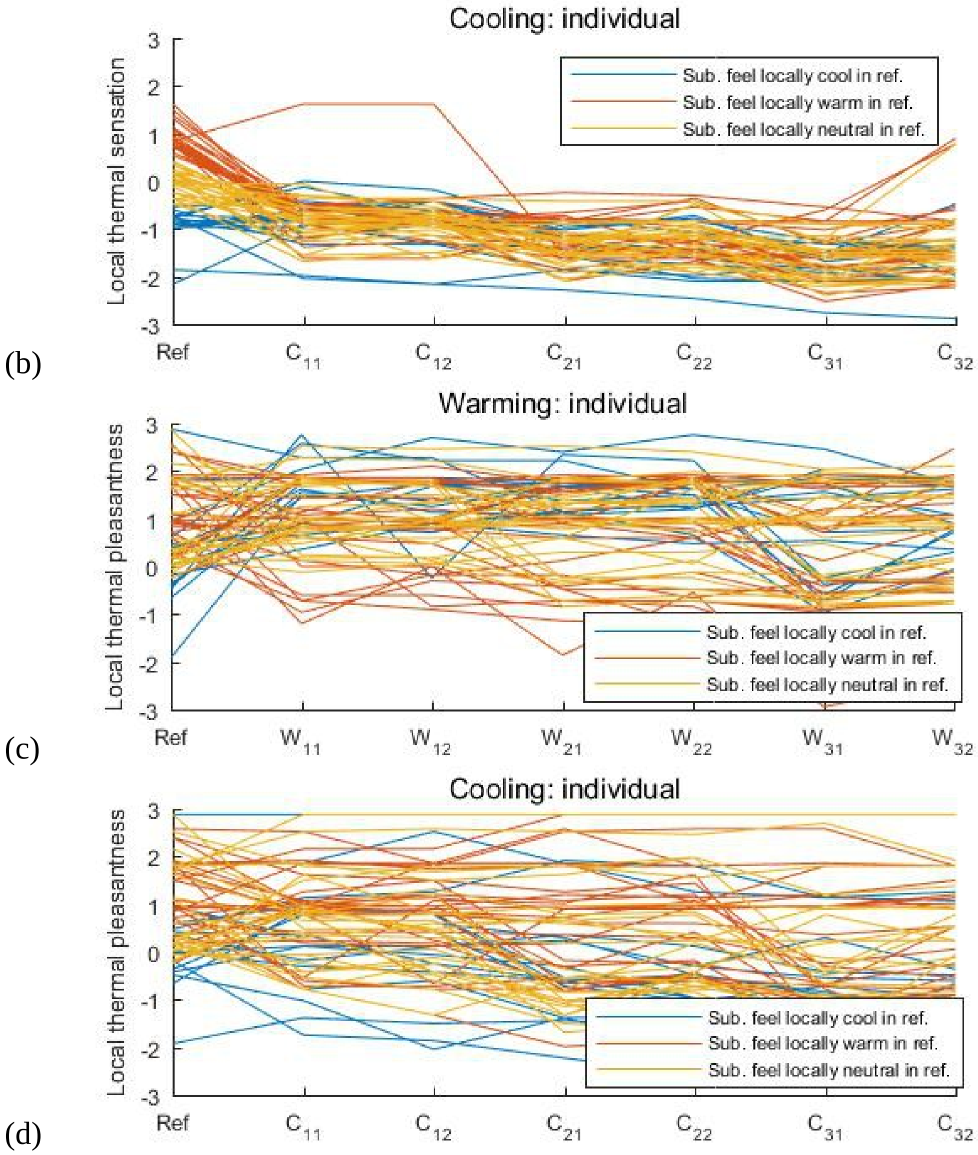


Figure 5. Local thermal vote with PCS: a) local thermal sensation of local warming, b) local thermal sensation of local cooling, c) local thermal pleasantness of local warming, d) local thermal pleasantness of local cooling

3.2 Effect of PCS

The effects of the local cooling and warming by the Wristband will be examined from three perspectives: local thermal sensation, whole body thermal sensation and whole body thermal comfort.

Statistical analysis of Figure 5 indicated that the local contact warming and cooling significantly changes the local thermal sensation, except for level 1 cooling with relatively low ambient temp (20ºC) and level 1 warming with relatively high ambient temp (26ºC). This indicates that local warming or cooling is not as effective when the local stimulus is in the same direction as the reference feeling. Another observation is that the local sensation becomes less strong in the second vote (90 seconds after the stimulus) than in the first vote (45 seconds after the stimulus).

Figure 6 depicts the effect of local warming and cooling on whole body thermal sensation. Because of the interpersonal differences, we cluster the subjects according to their whole-body thermal sensation (WBTS) votes without PCS under the reference conditions, including data from all three ambient condition tests. When subjects felt cool without the wristband, local warming could improve WBTS by 0.76 scale units ($p < 0.05$). When subjects felt warm without the wristband, local cooling could improve WBTS by 0.99 ($p < 0.001$). Considering the approximation that 1 WBTS scale unit difference corresponds to about 3K ambient temperature difference, local warming with 2W electricity consumption is providing a Corrective Power of 2K and local cooling with 2W electricity consumption provides a Corrective Power of 3K. When subjects felt neutral without PCS, both local cooling and heating could significantly change the whole body thermal sensation of the subjects. The changes are statistically significant, but less so than the changes in cool and warm people as mentioned above. Adding cooling to cool subjects, or adding warming to warm subjects, did not create significant impact (see the third bar in the first chart, and the middle bar on the third chart).

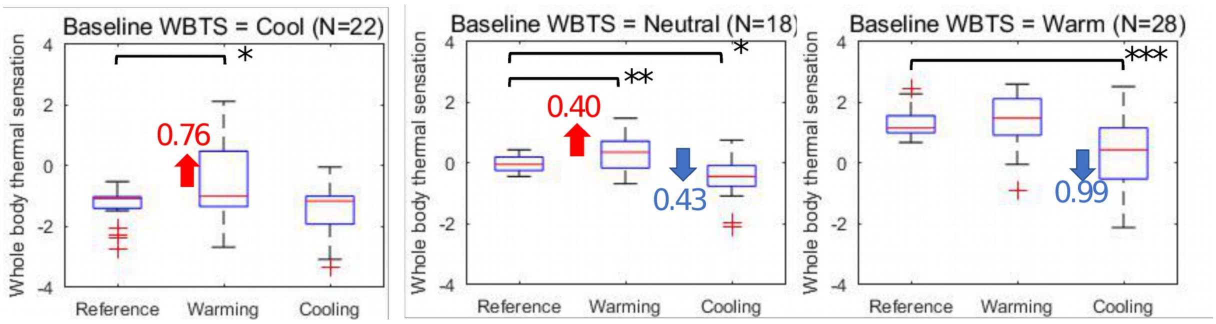


Figure 6. Whole body thermal sensation with PCS: clustering by whole body thermal sensation vote during reference condition.

The effect of wristband on whole body thermal comfort is illustrated in Figure 7. Similar to Figure 6, we separately grouped people for these who felt cool or warm discomfort under reference conditions, including data from all three temperature test conditions. When using warming feature, the wristband significantly improved cool discomfort subjects. The whole-body thermal comfort improved 0.86 scale unit. When using cooling feature, for the warm discomfort subjects, the wristband, also improved whole-body thermal comfort by 0.98 scale unit. Because there were only three people in this group, the result is not statistically significant.

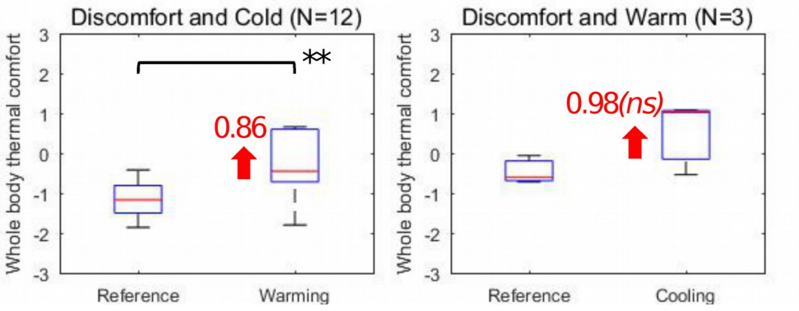


Figure 7. Whole body thermal comfort with PCS

4 CONCLUSIONS

This laboratory study explored the ability of a wearable thermal wristband device to improve whole-body thermal comfort of a group of subjects in three ambient conditions: 20, 23, and 26°C. Interpersonal differences in thermal comfort were clearly observed. Under these conditions, the wristband was able to significantly correct the whole-body thermal non-neutral sensation state. The wristband increased the whole-body thermal sensation by 0.76 scale unit for subjects who felt cool under the 20ºC reference condition, and reduced whole-body thermal sensation by 0.99 for subjects who felt warm under 26ºC reference condition.

Moreover, the wristband significantly improved the whole body thermal comfort of subjects who felt cool discomfort under reference condition by 0.86 scale units by the wristband. The wristband also improved the whole-body comfort for people who felt warm discomfort under reference condition, but there were only three people under this group, so the result is not statistically significant. These are impressive results for a device of such small cooling/warming area (25mm*25mm) and low electricity consumption (up to 2W). Their Corrective Power of 1~2K is comparable to that of larger PCS units such as fans that operate at the body segment scale.

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