Low-Energy Wearable Cooling Strategy for Thermal Comfort at a Warm Environment

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Summary

The objective of this study is to assess the effectiveness of wearable cooling in improving thermal comfort for a warm environment that would become prevalent due to more frequent extreme weather events, especially when air conditioning is not accessible for many developing countries. The experiment was conducted in an environment room with air temperature maintained at 31 °C and relative humidity at 55%. The study tested 30 participants using a wearable cooling device at the upper back location, while another 30 had no local cooling as the control group. Participants' thermal comfort, thermal sensation and other metrics were assessed three times for a test session. The clothing insulation was 0.36 clo to simulate summer attire. The results showed significantly lower average local and whole-body thermal sensation for the participants with the wearable cooling device than the control group by considering all the votes during the entire session. Compared to the baseline, in particular, the local cooling group indicated a significant reduction in local thermal sensation for all three times of self-evaluation. Nevertheless, the reduction in overall thermal sensation occurred right after the local cooling was applied. Such a significant reduction was not observed after a while and then emerged again during the test, indicating an interactive phenomenon involving thermal adaptation and comfort restoration which will be investigated in the future.

Introduction

Thermal discomfort has major effects on productivity, stress levels and energy consumption [[1] [2] [3]]. Furthermore, most buildings usually deliver a static thermal environment to most occupants which can carry significant power usage while not reaching the thermal comfort and work productivity desired [4]. Only 42% of occupants expressed satisfaction with the thermal environment [5] and it could be improved through personal comfort systems (PCS) [6]. PCS are devices that can offer local cooling or heating to users individually [6]. They provide an opportunity to reach thermal comfort with reduced energy penalty through a relaxed thermostat setpoint band and have the potential to satisfy individual thermal preference and adaptation without affecting the thermal comfort of other occupants in the same space. PCS comes in different forms which target different parts of the body. However, most existing personal comfort systems deliver heating and/or cooling using ergonomic devices (e.g., chairs) or relatively bulky personal items (e.g., vest with cooling packs). We propose a low-energy wearable cooling device that can be easily attached to a regular T-shirt to cool down the upper back/neck region that has been reported to be sensitive to cooling. This solution could offer an improvement in the overall thermal sensation, comfort, and acceptability of personnel in a non-neutral environment.

Materials and Methods

Low-Energy Wearable Cooling Device

Working with our industry partner (Embr Labs, Somerville, MA, USA), we sewed their ship flag product (Embr wave wristband) on the upper back of a T-shirt (Figure 1). The Embr wave wristband uses a thermoelectric (Peltier) heat pump to modulate temperature against the skin to generate precise and dynamic temperature profiles. A dynamic waveform of cooling or warming is delivered to the skin's surface through natural convection [6]. For this experiment, four Embr Waves were mounted to a t-shirt that serves as a wearable cooling device for the upper back. The inner surface of the device was directly contacted with skin by tailoring the T-shirt. The local cooling device provided oscillating cooling with a frequency of 0.2 Hz over the entire test session [7]. The neck region was chosen because upper back local cooling was reported to have the best effect compared to other body parts [8]. The selection of the position is also corroborated by another similar study concluding that local cooling of the neck may provide an effective way to increase local and overall thermal comfort during a heatwave [9].

Figure 1: *A subject of the local cooling group in a test session with the wearable cooling device. The inner surface of the device was directly contacted with skin by tailoring the T-shirt. The cable was connected to a fast-responsive skin temperature sensor.*

Methods:

The experiment was conducted in an environmental chamber at the Worcester Polytechnic Institute (WPI). A total of 60 university students (n = 35 males and n = 25 females) signed up for this experiment. The study tested 30 participants using the wearable cooling device, while the other 30 had no local cooling as the control group. A participant was randomly assigned to one condition. A summary of the participants' general characteristics in the two groups can be seen in *Table 1*. Statistical tests show no significant difference in the characteristics of the participants between the two groups. Participants were instructed not to consume alcohol, caffeine, nicotine the day of the experiment. They were also asked not to perform any strenuous exercise before a test.

Table 1. *Description of participants in the two groups (Mean ± SD)*

	Control Group (Female: 11; Male:19)	**Local Cooling Group (Female: 14; Male: 16)**	**p-value of the Mann Whitney test between two groups**
Age	20.39 ± 4.66	21.10 ± 2.11	0.23
Height (cm)	171.33 ± 9.84	172.47 ± 9.10	0.33
Weight (kg)	70.31 ± 12.58	69.43 ± 14.49	0.34
Exercise time (hr / week)	7.69 ± 6.45	6.58 ± 4.46	0.47

The environmental parameters were maintained at a steady level with air temperature at 31 °C, relative humidity at 55 %, Indoor CO2 level at 800 ppm, vertical luminance at 300 lux, and noise level at 60 dB. The clothing consisted of underwear, a t-shirt, shorts, socks, and walking shoes, giving standardized clothing insulation of 0.36 clo (including 0.07 clo from the chair). The t-shirt, shorts, and walking shoes were provided to all subjects by the experimenters, other clothing was brought by the subjects themselves. These parameters were chosen to simulate summer conditions with no air conditioning available, which results in a predicted mean vote of PMV of 1.25 [10].

Figure 2 illustrates the experimental protocol. Each test lasted for an average of 88 minutes for all participants. During the test, participants spent a 30 min thermal adaptation phase and then completed surveys to assess thermal environment and their comfort before the formal experiment. Then they completed six cognitive tests grouped in three sessions with each followed with the thermal comfort questionnaires. The only different procedure between the two groups lied in whether the wearable local cooling was applied together with the right-after questionnaires as described in Figure 2. The questionnaires immediately administered allowed us to capture any potentially temporal alliesthesia [11]. The results of cognition are out of the scope of this paper and will be published in the future.

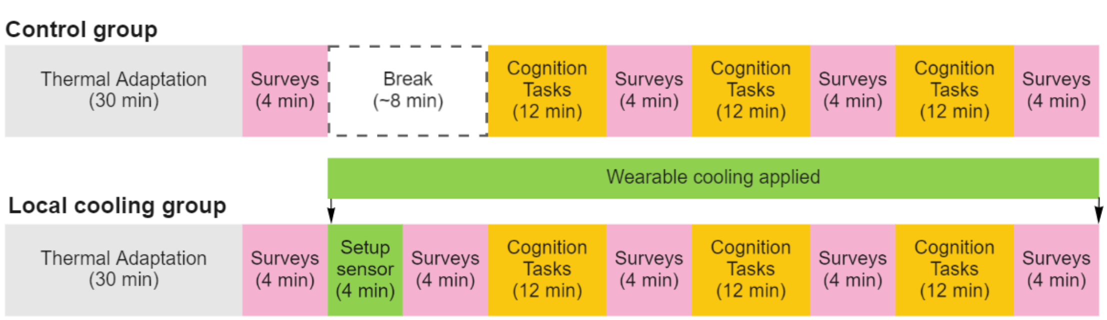

Figure 2: *Experimental Protocol for the control and local cooling groups*

The questionnaire used in this study contained thermal sensation, thermal comfort, thermal acceptability, and thermal preference for both the whole body and the local upper back where wearable cooling was applied. The participants answered a continuous scale thermal sensation raging from *Cold (-3)* to *Hot (+3).* A continuous scale (-3 to 3) with a broken range near the middle was employed for thermal comfort and acceptability. Thermal preference was also assessed on a continuous scale from -3 to 3.

Numerical results are presented as Mean ± Standard Deviation (SD) in the paper. The statistical analysis of data was completed using Python's library *SciPy* [12]. The Shapiro-Wilk normality test was used to verify the normality and homogeneity of the distribution of all questionnaire data, and all cognitive tests. Normally distributed data were subject to *t-Test*, otherwise. We used the *Mann-Whitney U test* as a non-parametric test for non-normally distributed data. Results were considered statistically significant at $p < 0.05$. The symbol "*" symbolizes a statistical significance of $p < 0.05$, whereas "**" symbol was used for $p < 0.01$, and "***" for $p < 0.001$. Furthermore, to assess the effect size of the difference, we used *Cohen's d-value* [14]. The thresholds by which the effect size was interpreted were $|d| < 0.147$ "negligible", $|d| < 0.33$ "small", $|d| < 0.474$ "medium", otherwise "large".

Results

Table 2 summarizes the statistical analysis of the responses to the survey on the overall and local thermal sensation, comfort, acceptability, and preference for the two groups. The statistical tests for the difference in the responses between the two groups are also described. The results showed that the local cooling can significantly reduce overall thermal sensation ($p= 0.03$), and local thermal sensation ($p = 0.001$). The average whole-body thermal sensations during the entire session were 1.37 ± 0.72 and 1.12 ± 0.90 for the control and local cooling groups, respectively. The wearable cooling device significantly reduced whole-body thermal sensation by 0.25 scale or 18%. Nevertheless, the reduction did not span across the test session equivalently. The lowest thermal sensation appeared right after the local cooling at the upper back was applied with an average whole-body thermal sensation vote of 0.87 ± 0.86 and local thermal sensation vote of -0.40 ± 1.37 for the local control group compared to the control group with an average of 1.26 ± 0.56 for the whole-body thermal sensation vote and of 0.71 ± 0.66 for the local thermal sensation vote, implying the occurrence of alliesthesia. However, the cooling effect attenuated with time until the 1st survey taking mainly due to thermal adaptation ($p = 0.41$). A significantly lower whole-body sensation for the local cooling group was observed at the 2nd survey ($p = 0.02$), and then the difference was tapering to the end of the session ($p = 0.43$). It seems that the participants with the local cooling experienced an oscillating whole body thermal sensation cooling that was unlikely caused by randomness. We hypothesize that the scenario was attributed to the interactive effect of thermal adaptation and comfort restoration, which warrants further investigation. As for the thermal sensation at the upper back, the local cooling device significantly reduced local thermal sensation across the whole session. Though effective in decreasing thermal sensation, the local cooling device was unable to significantly alter thermal comfort ($p = 0.13$ for overall vote and $p = 0.32$ for local vote), thermal acceptability ($p = 0.16$ for overall vote and $p = 0.41$ for local vote), or thermal preference($p = 0.06$ for overall vote and $p = 0.14$ for local vote), either overall or locally. The current device could be improved by increasing the skin contact area, namely, with more cooling modules on the upper back.

Table 2: Statistical summary of the whole body and local thermal evaluation for the two groups

Responses to the survey		Mean ± SD		P-value	t-test	Cohen's d
		Control Group	*Local Cooling Group*			
Thermal Sensation (Whole-body)	Pre	1.26 ± 0.56	1.34 ± 0.61	0.20	-	- 0.136
	Right-after	-	0.87 ± 0.86	**0.02***	-	0.537
	1st	1.24 ± 0.81	1.28 ± 0.67	0.41	-	-0.058
	2nd	1.51 ± 0.74	0.99 ± 1.03	**0.02***	-	-0.586
	3rd	1.40 ± 0.89	1.37 ± 0.85	0.43	-	-0.030
	All votes	1.37 ± 0.72	1.12 ± 0.90	**0.03***	-	0.302
Thermal Sensation (Upper Back)	Pre	0.71 ± 0.66	0.49 ± 0.79	0.195	-	0.298
	Right-after	-	-0.40 ± 1.37	**0.001*****	-	1.020
	1st	0.89 ± 0.54	0.16 ± 1.31	**0.017***	-	0.721
	2nd	1.15 ± 0.73	0.11 ± 1.29	**0.001*****	< **0.001 *****	0.987
	3rd	1.17 ± 0.90	0.30 ± 1.34	**0.005*****	**0.005 *****	0.756
	All votes	0.98 ± 0.73	0.04 ± 1.34	**0.001 *****	-	0.862
Thermal Comfort (Whole-body)	Pre	0.08 ± 0.96	0.10 ± 1.04	0.95	0.95	-0.016
	Right-after	-	0.21 ± 1.16	0.63	0.63	-0.125
	1st	-0.09 ± 1.39	-0.04 ± 1.36	0.31	-	-0.035
	2nd	-0.38 ± 1.56	0.10 ± 1.50	0.22	0.22	-0.317
	3rd	-0.20 ± 1.58	-0.25 ± 1.51	0.92	0.92	0.026
	All votes	-0.14 ± 1.39	0.01 ± 1.38	0.13	-	-0.114
Thermal Comfort (Upper Back)	Pre	0.64 ± 1.41	0.59 ± 1.11	0.87	0.87	0.041
	Right-after	-	0.20 ± 1.22	0.20	0.20	0.334
	1st	0.31 ± 1.31	0.05 ± 1.10	0.28	-	0.209
	2nd	-0.03 ± 1.44	0.18 ± 1.33	0.50	-	-0.107
	3rd	-0.10 ± 1.41	-0.03 ± 1.43	0.50	-	0.050
	All votes	0.22 ± 1.41	0.10 ± 1.26	0.32	-	0.088
Thermal Acceptability (Whole-body)	Pre	0.54 ± 1.21	0.68 ± 1.04	0.64	0.64	-0.122
	Right-after	-	0.57 ± 1.14	0.47	-	-0.025
	1st	0.27 ± 1.28	0.32 ± 1.30	0.49	-	0.036
	2nd	0.11 ± 1.45	0.56 ± 1.48	0.24	0.24	0.303
	3rd	-0.05 ± 1.91	0.10 ± 1.65	0.86	0.86	0.045
	All votes	0.24 ± 1.39	0.40 ± 0.39	0.16	-	-0.106
Thermal Acceptability (Upper Back)	Pre	0.85 ± 1.32	0.74 ± 0.94	-	0.71	0.095
	Right-after	-	0.67 ± 1.12	-	0.56	0.150
	1st	0.60 ± 1.29	0.61 ± 1.21	0.35	-	0.011
	2nd	0.56 ± 1.47	0.47 ± 1.41	-	0.81	-0.063
	3rd	0.03 ± 1.61	0.33 ± 1.49	-	0.60	0.137
	All votes	0.53 ± 1.37	0.52 ± 1.31	0.41	-	0.013
Thermal Preference (Whole-body)	Pre	-1.10 ± 1.16	-0.87 ± 1.21	0.12	-	-0.196
	Right-after	-	-0.92 ± 1.09	0.09	-	-0.159
	1st	-1.15 ± 1.13	-1.13 ± 1.21	0.27	-	-0.025
	2nd	-1.26 ± 1.07	-1.10 ± 1.22	-	0.60	0.136
	3rd	-1.22 ± 1.23	-1.21 ± 1.12	0.38	-	0.003
	All votes	-1.17 ± 1.15	-1.10 ± 1.13	-	0.06	-0.068
Thermal Preference (Upper Back)	Pre	-0.91 ± 0.86	-0.83 ± 0.90	0.31	-	0.091
	Right-after	-	-0.70 ± 1.10	0.195	-	-0.210
	1st	-1.02 ± 1.17	-0.95 ± 1.00	0.40	-	-0.063

2nd	-1.17 ± 1.03	-0.94 ± 1.19	-	0.43	0.202
3rd	-1.10 ± 0.94	-1.07 ± 1.15	0.92	-	0.027
All votes	0.95 ± -1.03	-0.93 ± 1.15	-	0.14	-0.094

Conclusions

The low-cost personal comfort systems can have a positive impact on thermal comfort in a warm environment with the minimum energy penalty. In this study, we investigated the effect of a wearable cooling device mounted on the upper back of a T-shirt on thermal comfort related metrics. This study showed that the local cooling device can significantly reduce whole body and upper back thermal sensation but have difficulties in improving thermal comfort or thermal acceptability or altering thermal preference. The effectiveness may be improved with more cooling modules at the upper back.

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