Perceived Cooling Using Asymmetrically-Applied Hot and Cold Stimuli

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Abstract—Temperature perception is a highly nonlinear phenomenon with faster rates of change being perceived at much lower thresholds than slower rates. This paper presents a method that takes advantage of this nonlinear characteristic to generate a perception of continuous cooling even though the average temperature is not changing. The method uses multiple thermal actuators so that a few are cooling quickly while the rest of the actuators are heating slowly. The slowly-heating actuators are below the perceptual threshold temperature change and hence are not perceived, while the quickly-cooling actuators are above the perceptual temperature change, hence are perceived. As a result, a feeling of decreasing temperature was elicited, when in fact, there was no net change in the temperature of the skin. Three sets of judiciously designed experiments were conducted in this study, investigating the effects of actuator sizes, forearm measurement locations, patterns of actuator layout, and various heating/cooling time cycles. Our results showed that 19 out 21 participants perceived the continuous cooling effect as hypothesized. Our research indicates that the measurement location, heating/cooling cycle times, and arrangement of the actuators affect the perception of continuous cooling.

Index Terms—Thermal sensation, continuous cooling, peltier cooler, thermal display, temperature perception.

1 Introduction

THERMAL sensation has the potential of virtually presenting information to a user and much of the research into this area has focused on using thermal feedback to increase the realism of teleoperation or virtual environment simulations by conveying the temperature of a remote or virtual object. For example, thermal cues can be used to discriminate between materials of different thermal properties [1]. However, the display of temperature in haptic and virtual environments is often excluded in practice because it is a relatively slow sense compared to tactile perception and also because the effects of temperature are confounded by many related tactile perceptions. But it is exactly these complex interactions that make it important to study. Skin temperature affects vibrotactile thresholds [2], calming music is associated with cooling skin [3], and body temperature can even affect the performance of athletes [4]. Yet, the ability to use a thermal actuator to generate a perception in a person lags behind the use of force and tactile feedback.

Skin contains different sensors that measure hot and cold, and the perception is highly dependent upon the rate of temperature change [5]. We hypothesize that multichannel dynamic temperature inputs will enable unique temperature display capabilities because a slower rate of temperature change causes a nonlinear increase in warm and cold thresholds [6]. By arranging a grid of independently controlled temperature actuators, one or more actuators can always be cooling quickly while the others are heating slowly as shown in Figure 1. Alternating which actuator/actuators are cooling quickly ensures that the average skin temperature never changes yet, the person will perceive that their skin is continuously cooling due to the nonlinear temperature perception. This method is conceptually similar to using an asymmetrically applied oscillating force that generates a perception of force applied in one direction, but without any net force applied [7]. To achieve this thermal pattern, we use thermoelectric devices (also known as Peltier coolers). They work as heaters or coolers under an applied voltage with different polarities. Thermoelectric devices are well-suited to applying dynamic temperature inputs [8]. They can easily be scaled to small sizes because no moving parts are required. If one side is held at a relatively constant temperature, the other can be made cooler or hotter in proportion to the applied voltage.

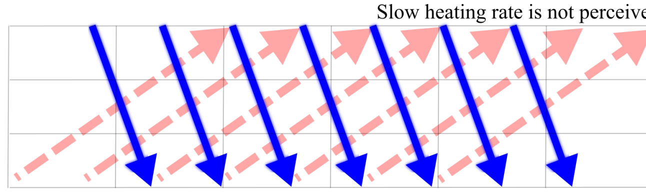

Fig. 1. Slowly heating actuators mixed with quickly cooling actuators create the feeling of continuous cooling.

The purpose of this work is to investigate our hypothesis that a perception of cooling can be conveyed without actually changing the average skin temperature, and to examine how the body can perceive and integrate multiple dynamic localized temperature changes (from Peltier devices in these experiments). These results provide a new insight into the spatial summation process and could enable the rational design/development of thermal display systems for a wide range of applications.

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2 Background on Thermal Perception

Human skin detects the changes in temperature by thermoreceptors located in the dermal and epidermal skin layers. There are two types of thermoreceptors: warm receptors, which are active for temperature increases from 30°C to 45°C, and cold receptors, which are active for temperature decreases from 30°C to 18°C. Cold receptors outnumber warm receptors in the skin by a ratio up to 30:1 [9] [10]. Additionally, cold receptors respond faster than warm receptors. Wilson [11] found that cold stimuli can be detected faster than warm stimuli. Between 30°C and 36°C, both warm and cold thermoreceptors are active, and no thermal sensation is observed at steady state [12]. Below 18°C and above 45°C, pain receptors, called nociceptors, are active [13].

According to Jones and Ho [14], temperature perception depends on the rate of temperature change, magnitude, baseline temperature of the body, and the stimulated location on the body. One typical metric of sensitivity is the threshold at which the stimulus is first perceptible. For example, a slow temperature change will not be noticed until the temperature has increased by over 3°C and temperature sensitivity increases up to 0.1°C/s, where the temperature change is noticed after about a 0.4°C change; further increasing the rate beyond 0.1°C/s has a small effect on the thermal threshold [15] [16]. The relationship between the temperature threshold and the rate of temperature change is shown in Figure 2. The different sensations of cold and warm are usually associated with the conduction velocities of cold receptors, which respond much faster than warm receptors [12].

The area of the simulation is inversely related to the thermal threshold of the skin where the temperature change is first noticed. In fact, low spatial resolution of thermal stimuli occurs because the sensed temperature is based on the spatial average of stimuli over an area or feature of the body [18]. Spatial summation effects decrease the thermal threshold as the area of thermal stimuli increase. Smaller temperature differences can be detected by increasing the thermal stimuli area [19]. Increasing the area of warm stimulus has more effect on thermal threshold than increasing the area of cold stimulus [15]. Spatial summation implies that tests of perception should be performed on large areas of the skin. In order to apply thermal gradients to the skin without causing effects from the coverage, the area needs to be large enough so that there is not a significant size effect.

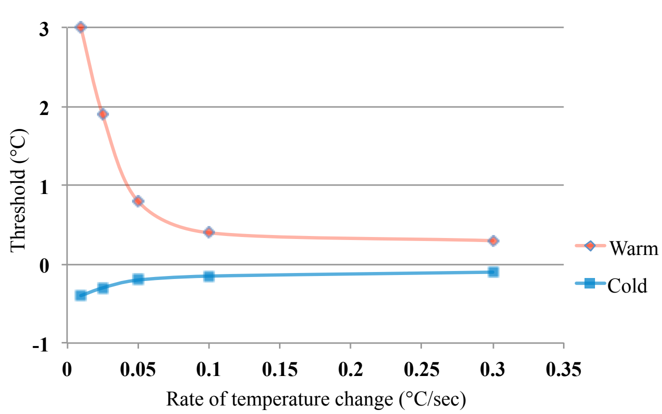

Fig. 2. The rate of change affects the thresholds at which temperature changes are first noticed. Data adapted from [16] and [17].

Studies have shown that large differences in nearby temperatures can confuse thermal perception [20]. Low temperature differences elicit a feeling referred to as synthetic heat [21]. Synthetic heat is generally perceived when adjacent hot and cold sensors perceive a discrepancy. Thunberg [22] first discovered this effect and called it the thermal grill illusion. Although synthetic heat and the thermal grill illusion terms are often used interchangeably because the resulting effect is the sensation of strong heat, synthetic heat usually refers to applying equal amounts of heating and cooling to the skin sequentially, whereas the thermal grill illusion typically refers to the heating and cooling of the skin in alternating rows. These effects often diminish after a short time [23]. The thermal grill illusion and synthetic heat are often related to the sensation of pain. However, it has been shown that synthetic heat can be perceived without pain by applying cool and mildly warm stimuli [24].

The method tested here is distinctly different than the thermal grill illusion and synthetic heat in that all of the actuators' temperatures are constantly changing and the application rates of heating and cooling are asymmetric. Furthermore, this method applies a 1°C temperature difference between heating and cooling stimuli unlike synthetic heat and thermal grill where the temperature difference can get up to 20°C between heating and cooling stimuli [25]. Also, in this method, the actuators are continuously changing directions between heating and cooling unlike the thermal grill illusion where each actuator has a constant temperature and does not change direction between heating and cooling.

3 Method

This study consisted of three sets of experiments evaluating different aspects of the continuous cooling perception. The first experimental set investigated the differences between the application of a four-channel dynamic thermal display with two patterns and constant skin temperature. The second experimental set employed a twelve-channel dynamic thermal display to investigate its effect on three locations by applying different heating/cooling rates. The third experimental set tested the effect of multiple thermal patterns on the perception of continuous cooling using the twelve-channel dynamic thermal display.

3.1 Thermal Stimuli

In experimental set 1, two patterns of stimuli, shown in Figure 3(a), were applied to the subjects to test how the pattern of thermal actuation affected the perception. The ordered pattern sequentially increased the temperature of the actuators in order across the forearm so that each location felt a delayed version of the adjacent actuator. The rearranged pattern mixed up this consistent pattern so the adjacent actuators were out of sync with each other. In these two dynamic patterns, four actuators were controlled such that three were slowly heating over 30 seconds out of phase with each other at a rate of 0.033°C/s and one was quickly cooling over 10 seconds at a rate of 0.1°C/s. Every ten seconds, the actuator that was cooling would start slowly heating up and another would start quickly cooling. This heating/cooling cycle will be referred to as 30/10, which corresponds to the pattern each actuator follows throughout the experiments. The third thermal stimulus in experimental set 1 applied a constant temperature as a neutral temperature reference point baseline for comparison. In this baseline, all actuators were maintained at 31°C for four minutes during this control stimulus, which is the same time duration and average temperature as the dynamic actuation.

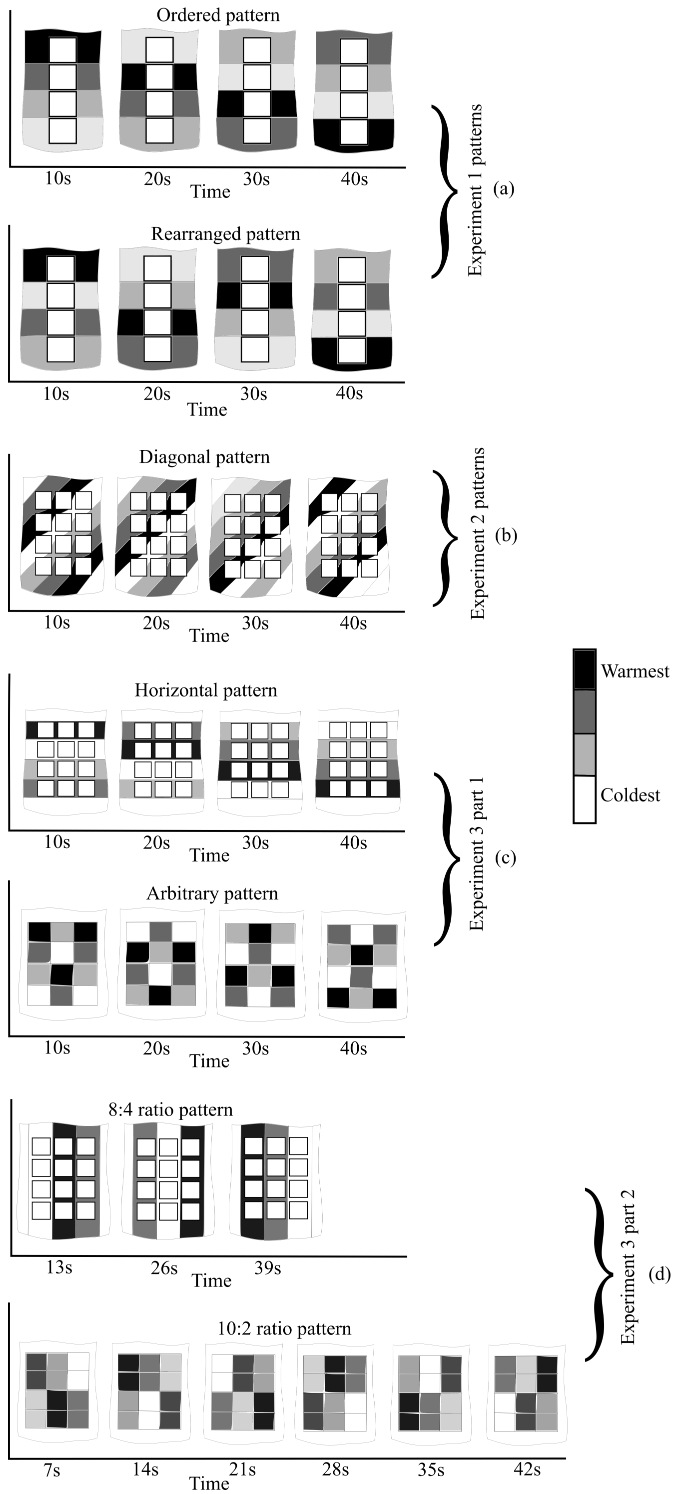

Fig. 3. All experimental patterns with cycle time in seconds.

Experimental set 2 investigated the same concept using twelve actuators so additional configurations could be evaluated. Nine actuators were slowly heating out of phase with each other and three were quickly cooling. Three different heating/cooling cycles were used with one diagonal pattern. The first cycle was the 21/7, where nine actuators were slowly heating over 21 seconds (at a rate of 0.047°C/s) and three were cooling over 7 seconds (at a rate of 0.14°C/s). The second cycle was the 45/15, where nine actuators were slowly heating over 45 seconds (at a rate of 0.022°C/s) and three were cooling over 15 seconds (at a rate of 0.067°C/s). The third cycle was the 30/10. Figure 3(b) shows the thermal pattern for experimental set 2 (with an example rate of 30/10).

Experimental set 3 was conceptually divided into two parts examining different aspects of the thermal perception, but was performed during the same subject session. In the first part, three different patterns were tested with the 30/10 heating/cooling time. The patterns were diagonal, horizontal, and arbitrary as shown in Figure 3(c). In the second part, two additional heating/cooling ratios were tested. The first ratio was 8:4 where eight actuators were slowly heating and four were quickly cooling in a vertical pattern. The second ratio was 10:2 where ten actuators were slowly heating and two were quickly cooling. Figures 3(c) and (d) illustrate all the patterns tested in experimental set 3.

All the heating/cooling rates from all three experimental sets were based on the data from Figure 2 and are selected so that the cooling will be above the perceptual threshold and the heating will be below the perceptual threshold. For instance, a rate of 0.033°C/s is large enough to raise the temperature of the actuator 1°C, but is small enough to not trigger the perception of warming. Table 1 summarizes the different heating/cooling time cycles and patterns used in all three experimental sets.

The average surface temperature stayed constant in all trials during the experiments even though each actuator changed linearly between 30.5°C and 31.5°C in most cases. The actuators with increasing temperatures were under the rate threshold, whereas the actuators with decreasing temperature were above the threshold and, thus, noticeable. Before starting the patterns, all actuators were slowly warmed up to the normal skin temperature (which is approximately 31°C) [6].

TABLE 1
Time rates and patterns used in the experiments

	Warming/cooling time	Pattern	Location
Experiment 1	30/10	Ordered	Right anterior forearm
	30/10	Rearranged	
Experiment 2	21/7	Diagonal	Right/Left anterior/posterior forearm
	30/10		
	45/15		
Experiment 3 part 1	30/10	Horizontal	Right posterior forearm
	30/10	Diagonal	
	30/10	Arbitrary	
Experiment 3 part 2	26/13	Vertical	Right posterior forearm
	30/10	Diagonal	
	35/7	Diagonal	

3.2 Apparatus

In experimental set 1, four large thermal actuators were used. The actuators were peltier devices (40 mm x 40 mm x 3.8 mm) (Vktech TEC1-12706) mounted on an aluminum plate (80 mm x 200 mm x 4 mm). Two heat sinks (98 mm x 40 mm x 20 mm) were attached under the plate. Four surface-temperature thermistors (Mindray MR403) were attached to the surfaces of the peltier devices using double-coated thermal tape. A foam pad surrounded the peltier plates to ensure the heat transfer occurred through the peltier plates and not the surrounding portion of the plate or arm. Figure 4 shows the experimental setup.

Twelve thermal actuators were used in experimental sets 2 and 3. The actuators were peltier devices (14.8 mm x 14.8 mm x 3.6 mm) (TE-31-1.0-1.3). The actuators formed a 3 x 4 thermoelectric matrix with a 7.5 mm space between the actuators. Twelve thermistors were used to control each actuator individually. To provide accuracy in temperature reading, each thermistor was inserted inside an aluminum plate (15 mm x 15 mm x 3 mm). The aluminum plates were attached to the surface of the peltier devices using thermal paste. Every four actuators were attached to a heat sink (98 mm x 20 mm). A simple voltage divider circuit was added to the apparatus to read the thermistors. The 3 x 4 matrix with the heat sinks, aluminum plates, thermistors, and the voltage divider circuit were built on a cellphone armband as shown in Figure 5 to add maneuverability to the apparatus. The total stimuli area was $48.53\,\text{cm}^2$.

The actuators were driven with a proportional feedback controller. After receiving the temperature readings from the thermistors, the controller calculated the required current for the peltier devices. The control signal was sent via serial port to an op amp in a voltage-controlled current source configuration. Figure 6 shows the proposed pattern against the actual temperature pattern applied on one of the subjects. The actual pattern ranged between 30.5°C to 31.5°C, which is slightly smaller than the proposed range, but sufficient for these tests.

The actuator board in experimental set 1 was designed in a way that allowed subjects to lift their arms at any time during the experiments in case they felt uncomfortable or in case of an emergency. We noted that some subjects moved their arms around during the experiments. Two subjects even lifted their arms completely off the actuators during experimental set 1 for none of these reasons. That motion caused some disturbance with the surface temperature of the actuators. However, the apparatus used in experimental sets 2 and 3 addressed the arm-movement issue by strapping the apparatus to the forearm to ensure full contact between the actuators and the skin. Because it was difficult to remove quickly, proper caution was taken to avoid any electrical contact or excessive temperatures. The amount of pressure applied from the actuators on the skin

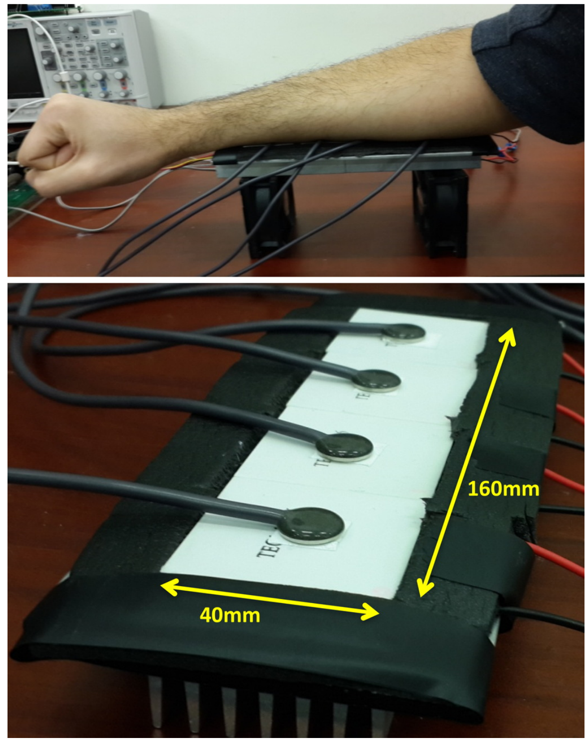

Fig. 4. The device used in experimental set 1 to test the constantly changing thermal patterns on humans.

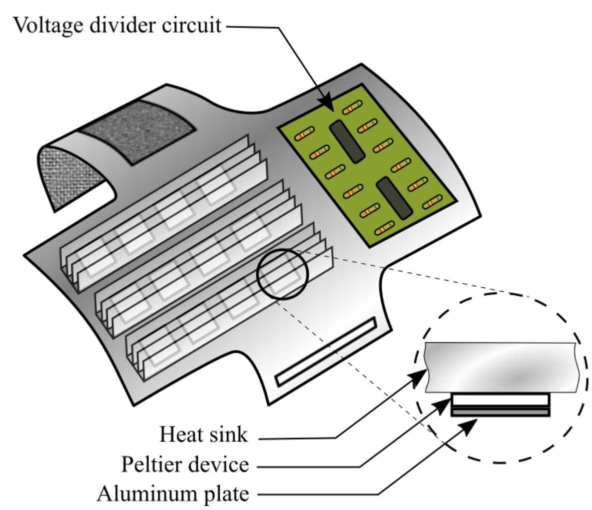

Fig. 5. The device used in experimental sets 2 and 3 to test the constantly changing thermal patterns on humans.

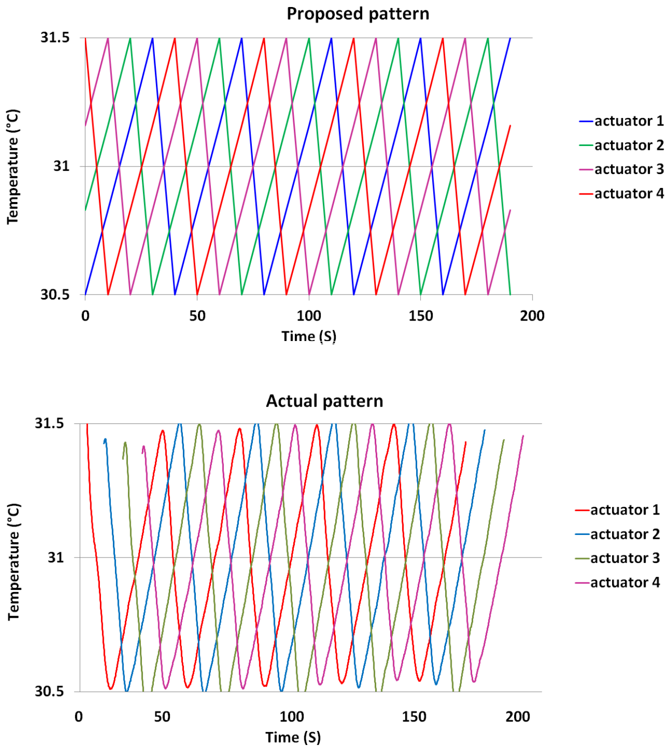

Fig. 6. Proposed pattern (top) compared to the actual pattern applied on one of the subjects (bottom).

has been shown to not have significant effects on thermal thresholds or perception [26], hence, we did not consider it in our current investigation.

3.3 Experimental Procedure

In all three experimental sets, subjects were seated in a chair and were offered a brief explanation of the study followed by the consenting process. Following that, the temperatures of their anterior and posterior forearms were measured using a non-contact laser temperature gun.

Experimental set 1 was divided into three phases: the ordered pattern, the rearranged pattern, and the constant temperature. At the beginning of each phase, subjects were asked to press the anterior area of their dominant forearm against the actuators. Subjects were instructed to keep their forearms in continuous contact with the actuators for the entire four minutes of each phase. Each subject in experimental set 1 did a total of three randomly ordered experiments in an average of 30 minutes.

Experimental set 2 was also divided into three phases: 30/10, 21/7, and 45/15 heating/cooling time cycles, all in a diagonal pattern. Three different locations were tested: the posterior and anterior dominant forearm and the anterior non-dominant forearm. Subjects received assistance to wear the apparatus on their forearms. Each subject in experimental set 2 completed a total of nine randomly ordered experiments in an average of 1 hour.

To better describe experimental set 3, it was conceptually divided into two parts. The first part consisted of three phases: 30/10 diagonal, 30/10 horizontal, and 30/10 arbitrary. The second part consisted of two phases: 8:4 and 10:2 heating/cooling ratios. These two parts will be combined in the results section for analytical purposes. Subjects received assistance to wear the apparatus on their posterior dominant forearm. Each subject in experimental set 3 completed a total of five randomly ordered experiments in an average of 30 minutes.

TABLE 2
Thermal sensation scale used in the experiments

Value	Thermal scale
+3	Hot
+2	Very warm
+1	Warm
0	Neutral
-1	Cool
-2	Very cool
-3	Cold

To allow initial transients to settle, the first minute of each phase was not analyzed in all experiments and subjects were told to wait until after this warm-up phase before responding. Throughout the last three minutes of the experimental phases, subjects were asked to describe how they perceived the temperature of their arm. In experimental set 1, the participants were asked every 30 seconds, which corresponded to the point where two actuators are at the lowest and the highest temperatures. In experimental sets 2 and 3, different patterns and heating/cooling ratios were being implemented, hence, a question every 30 seconds would not meet similar peak points. Instead, a question every 22 seconds in experimental sets 2 and 3 was used to ensure the consistency of the effect between all three experimental sets. Subjects' responses were quantified using the scale shown in Table 2, which is a slightly altered form of the American Society of Heating, Refrigeration, Air-conditioning Engineering (ASHRAE) thermal sensation scale [27]. Subjects would take a five minute break between each experimental phase. During the break, subjects were asked to describe if they felt a temperature change and if there was any differences between the phases.

3.4 Subjects

All subjects were between 18 and 55 years old, healthy, right handed, and their average arm skin temperature generally ranged between 30°C and 32°C. All experiments were conducted in a room with a temperature of 22°C. Each participant read and signed a consent form before the experiment that followed a protocol approved by the University of South Florida's Institutional Review Board.

A total of 21 subjects participated, but a technical malfunction occurred during one experiment, so this subject's data was not analyzed. The subjects were distributed as follows: Ten subjects participated in experimental set 1, seven males and three females. Eight subjects participated in experimental set 2, seven males and one female. Three of them had participated in experimental set 1. Another eight subjects participated in experimental set 3, six males and two females. Two of them had participated in the previous experiments. Only one subject participated in all three experiments.

4 RESULTS

A chi-square goodness-of-fit test was performed on all conditions of the experimental sets to determine whether the data were randomly sampled from a normal distribution. The results showed that the data were not normally distributed in any of the experimental sets. Therefore, a comparison of the repeated measures using Friedman's test was performed to analyze the data in each experimental set. When the Friedman test yielded significant results, a Wilcoxon Rank-Sum Test was used as the post-hoc test for individual comparisons. The results are illustrated using the means and standard errors of the factors in the experimental sets.

In experimental set 1, the non-parametric Friedman's test showed a statistically significant difference between the three experimental patterns ($X^2(2) = 37.98$, $p < 0.001$). A post-hoc test showed that the constant temperature control was statistically significantly different than the ordered pattern ($Z = -3.93$, $p < .0001$) and rearranged pattern ($Z = -3.27$, $p < .0001$), but there was no statistically significant difference between the ordered and rearranged patterns. Moreover, there was a clear perception of a continuous cooling effect in 9 out of the 10 subjects. The analysis did not show statistical significance between the answer timings. However, subjects reported that the location of cooling moved around the arm during the experiments. Only one subject perceived a sensation of heating during the ordered/rearranged patterns. The subject that did not perceive the continuous cooling was the only subject with a relatively low skin temperature ranging between 29°C (close to the wrist area) and 30°C. The thermal response results for all subjects are illustrated in Figure 7.

All subjects in experimental set 1 reported that the temperature did not change during the constant temperature phase. Eight subjects reported that both the ordered and rearranged sequences were generally cool. Seven of them stated that the ordered pattern was colder than the rearranged pattern. Furthermore, two subjects performed the experiments on their posterior forearms in addition to the anterior side. However, we did not continue this version of the experiment because the subjects reported discomfort in positioning the dorsal area of their forearms horizontally on the actuators for four minutes.

In experimental set 2, Friedman's test yielded statistically significant results between the heating/cooling times ($X^2(2) = 15.72$, $p < 0.001$), and between locations ($X^2(2) = 17.74$, $p < 0.001$). The test did not show statistically significant differences between the answer timings. A post-hoc test showed that the 45/15 heating/cooling time is statistically significantly different than the 30/10 ($Z = -2.99$, $p = .003$) and 21/7 ($Z = -2.62$, $p = .009$) as illustrated in Figure 8. The perception of continuous cooling was reported from 7 out of the 8 subjects. Three subjects, who also participated in experimental set 1, reported that the cooling felt steadier and more spread out than it was in experimental set 1. One subject did not perceive a continuous cooling or heating sensation during the experiment. A post-hoc test, illustrated in Figure 9, shows that the dominant posterior forearm location was statistically significantly different than the nondominant anterior location ($Z = -4.24$, $p < .001$) and the dominant anterior location ($Z = -3.12$, $p = .002$). Subjects did not report any differences in the perception between the anterior locations of both forearms.

The analysis of experimental set 3 yielded statistically significant differences between the combinations of pattern/ratio stimuli ($X^2(4) = 10.36$, $p < 0.05$) and between the answer timings ($X^2(7) = 24.95$, $p < 0.001$). A post-hoc analysis showed that the diagonal 10:2 ratio was statistically significantly different than both the horizontal 9:3 ratio ($Z = -2.13$, $p = .033$) and the vertical 8:4 ratio ($Z = -2.50$,

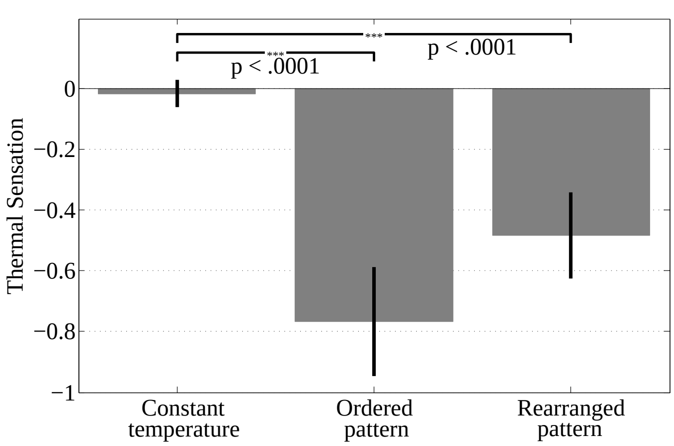

Fig. 7. Experimental set 1 results showing means and standard errors for the different patterns. Ordered and rearranged patterns are statically significantly different than the constant temperature condition.

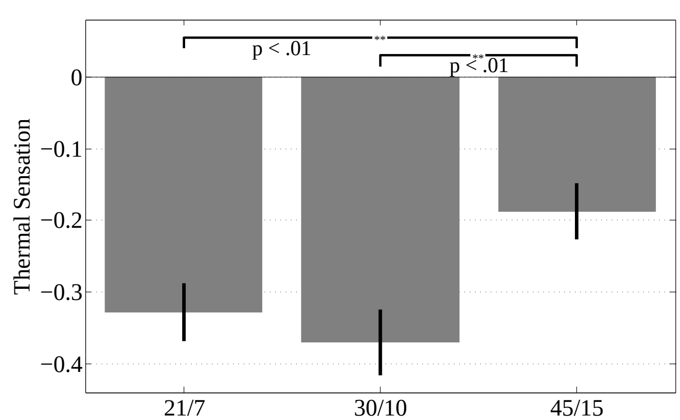

Fig. 8. Experimental set 2 results showing means and standard errors for the different cooling rates. 45/15 heating/cooling time is statistically significantly different than 30/10 and 21/7 times.

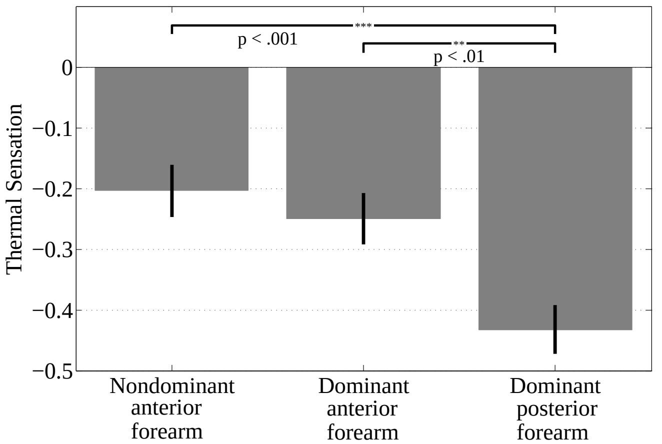

Fig. 9. Experimental set 2 results showing means and standard errors for the location of thermal stimuli. The perception on the posterior forearm is statistically significantly different from the perception on the anterior forearms.

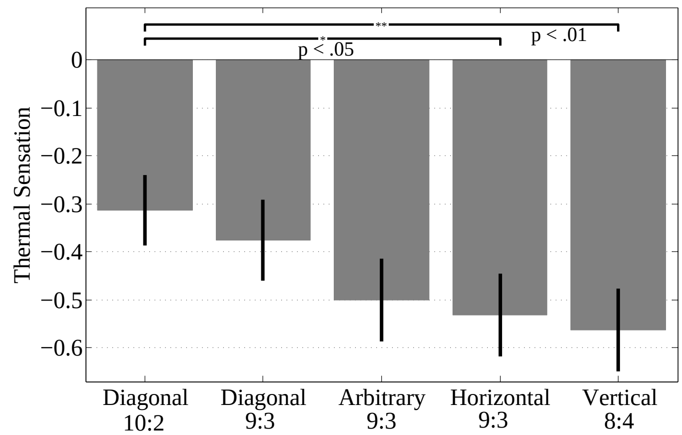

Fig. 10. Experimental set 3 results showing means and standard errors of the patterns and ratios. The perceptions of the 8:4 and horizontal 9:3 heating/cooling ratios were statistically significantly different than the 10:2 ratio. Also, all results were statistically significantly different than zero.

$p = .01$) as illustrated in Figure 10. Furthermore, time2 in the answer timings was statistically significantly different than time5 ($Z = -3.02$, $p = 0.003$) and time8 ($Z = -3.41$, $p = 0.001$). Time8 was also statistically significantly different than time3 ($Z = -2.84$, $p = 0.005$) and time4 ($Z = -2.6$, $p = 0.009$), as shown in Figure 11.

5 DISCUSSION

The experiments showed that subjects were generally able to perceive a sensation of continuous cooling. However, most of the subjects reported that the location of the cooling moved around the arm throughout experimental set 1. The large surface area of each actuator and lack of interspersing of the channels likely caused this perception of moving. Lee et al, showed that cooling stimuli are localized significantly better than warming stimuli [28]. It was also shown that, for warm thermal stimuli, spatial localization is usually very poor on the forearm [29], which may account for this moving perception of cooling.

Interspersing the thermal actuators increases the effectiveness of the continuous cooling sensation. Experimental set 2 offered a further study of this observation by increasing the number of the actuators from four to twelve while decreasing the size of each actuator from $16\,\mathrm{cm}^2$ to $2.25\,\mathrm{cm}^2$. By decreasing the surface area of each actuator and interspersing them, the nine out of ten subjects that perceived cooling in experimental set 2 reported a locally fixed feeling of cooling. Sato [30] studied a thermal display on relatively small, spatially divided peltier devices and the results showed that small skin areas can perceive thermal stimulations effectively. Also, decreasing the area of stimulation may have a slight effect on the cooling intensity, however, cold thresholds are less dependent on the area compared to warm thresholds [15] [31].

The patterns of stimulation also showed a slight effect on thermal perception in experimental set 1. Seven out of

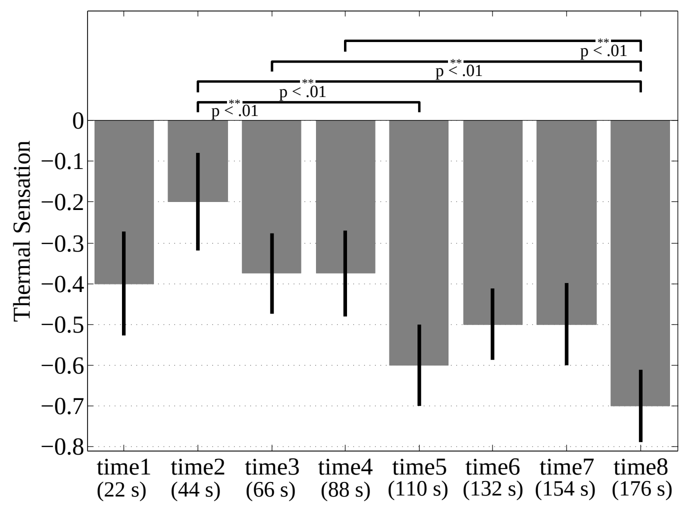

Fig. 11. Experimental set 3 results showing means and standard errors of the answer timings. The horizontal axis shows the time at which subjects were asked in seconds. Time8 was statistically significantly different than time2, time3, and time4. Time2 was statistically significantly different than time5. All results were statistically significantly different than zero.

ten subjects reported that the ordered pattern was cooler than the rearranged pattern. This can be explained by the locations of the coolest and warmest actuators during the patterns shown in Figure 3. In the ordered pattern, the actuator with the lowest temperature was next to the one with the highest temperature for 30 uninterrupted seconds out of each 40 second cycle, which created a relatively high temperature difference applied on a relatively small surface area. In the rearranged pattern, the lowest and the highest actuator temperature were next to each other for only 20 seconds divided on two separate intervals of 10 seconds each. This implies that the local temperature gradient has a significant effect on the consistency of the continuous cooling perception.

Previous studies showed that warm thresholds decrease with faster rates of temperature change [6]. However, experimental set 2 showed that 30/10 and 21/7 heating/cooling rates were perceived as significantly colder than 45/15, even though it had the slowest rate of change at $0.022°C/s$. Moreover, subjects reported a better cooling perception in the 21/7 rate even though the heating rate of change was the fastest at $0.047°C/s$. Harding and Loescher [32] tested different rates of stimulus change up to $1°C/s$ with a 16×16 mm peltier device and indicated that a faster rate of stimulus change can invoke a thermal adaptation to the warming stimulus. However, they did not find adaptation in cooling stimulus with the different rates of stimulus change. Thus, subjects may have adapted to the warming stimulus during the 21/7 and 30/10 rates.

This study found a difference in the perception based on the location of applied stimulus. In experimental set 1, two subjects performed the experiments on their posterior forearms in addition to the anterior side. However, both subjects reported discomfort in positioning the dorsal area of their forearms horizontally on the actuators for four minutes. Additionally, their forearms were not in full contact with the actuators due to the unusual angle, thus, we did not continue this version of experimental set 1 and their data were discarded. The apparatus used in experimental sets 2 and 3 helped us perform additional tests on the posterior area of both left and right forearms of the subjects. The results showed a significantly colder sensation on the posterior forearms. Stevens [33] found that thermal sensitivity varies 100-fold between body parts. Other studies have shown that dorsal and ventral areas on the hand and the forearm have different thermal sensitivities [34].

The results from experimental set 3 showed significant differences between different answer times. Such differences were not found in experimental sets 1 and 2 since they were conducted using the same heating/cooling ratio but with different patterns, locations, and heating/cooling times. However, different heating/cooling ratios were used in experimental set 3 which means that, at a certain time period, subjects reported an answer while perceiving cold from two, three, or four actuators based on the experiment's ratio. Figure 11 shows that the perception of cold may not be as consistent during the transient periods of the experiments, however, the perception becomes relatively more consistent and intense after that. To better address the effect of timing, more question timings should be tested to verify that the perception of cold is not consistent during a time period. This inconsistency in perception can also be avoided by overlapping the cooling periods of the actuators such that next actuator reaches the perception threshold of cold about the time that the first one is switching to heating without causing a change in the average temperature on the area of stimulation.

To compensate for the difference between heating/cooling ratios in experimental set 3, the heating/cooling times for the 8:4 and the 10:2 ratios had to be modified from the original 30 second heating and 10 second cooling. Instead of keeping the warming time constant and changing the cooling time (for instance 30 second warming and 15 second cooling for the 8:4 ratio), we chose to change both warming and cooling times in a way that keeps both times (26 second heating, 13 second cooling) close to the original 30 second heating and 10 second cooling. The same concept was used to determine the heating/cooling times for the 10:2 ratio where the time cycles were set as 35 second heating and 7 second cooling. Investigating different heating/cooling ratios with a constant warming or cooling time may determine whether the driving factor of the localized thermal perception is governed by warm or cold stimulus. Melzack [35] found that a continuous cold stimulus reduces the skin sensitivity to cold while warm stimulus increases it, which suggests the maximum time for cooling should be limited.

Based on the data shown in Figure 2, relatively slow temperature rates of change should not trigger the warm thermoreceptors. However, during experimental set 1, we found that a $1°C$ increase can sometimes be sensed even with a low rate of change like $0.033°C/s$. We also investigated different rates of temperature change in experimental sets 2 and 3 ranging from $0.022°C/s$ to $0.047°C/s$ and found that a $1°C$ increase was not sensed. This is likely related to the dependence of temperature perception on the heat flux transferred between the actuators and the skin [36] and to the area of stimulation [15]. This is, however, challenging to control since heat flux is based on the temperature differential between the lower layers of skin and the thermal actuator. A better option to relate the applied heat to the perception in dynamic environments is a flux meter that could be constructed by placing two resistance temperature detectors (RTD) on either side of a thin film of material of known thermal conductivity. The temperature sensor pair would measure the thermal flux entering the skin to test how absolute temperature and heat flux affect thermal perception. There would be some delay associated with this measurement because the thermal receptors measure the heat flux at a distance below the skin, but this difference should be negligible over the time scales that will be studied.

Most thermal display applications provided a thermal feedback using hot or cold stimuli. These stimuli often apply relatively large temperature differences on the skin. Salminen [37] found that a $6°C$ change on the skin temperature was unpleasant, arousing, and dominant. In other cases, a combination of hot and cold stimuli, like the thermal grill illusion and synthetic heat, were used to convey thermal information. These combinations also apply large temperature differences on the skin and often diminish after a short time, typically around 10 seconds [23]. The method presented here can apply a continuous cooling sensation without changing the average temperature of the area of stimulation for substantially long periods as illustrated in Figure 11.

Peltier devices were very effective and efficient to use as actuators in this study. However, with continuous use, the heat build-up in the devices caused difficulties when cooling the actuators after prolonged periods of time. Small differences can be observed between the different actuators in Figure 6 even though the same controller properties were used. As an alternative, small hot and cold liquid channels with controlled valves could replace the thermoelecric device system. Hot and cold water would be mixed to the desired temperature and run through small tubes that are in contact with the skin. The system could easily cover relatively larger skin areas and its temperature could be controlled precisely. There will however be some difficulties in routing all of the water tubes since they are typically less flexible than electrical cables.

6 Conclusion

We presented four-channel and twelve-channel dynamic thermal displays that were used to create the sensation of continuous cooling without a change in the average temperature of the area of stimulation. We focused on the interaction of a relatively large area of skin with multiple nonlinear localized temperature changes. The study consisted of three different sets of experiments. Twenty one subjects participated in a total of 142 sessions. The results showed that subjects were generally able to perceive continuous cooling. The study demonstrated the possibility of testing thermal perception without causing a net change in the actual thermal state of the skin.

There are several planned future works and improvements that could be pursued for this study including measuring the heat flux instead of the surface temperature to control the actuators. These changes will likely lead to an improved and more robust perception.

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