Asymmetric Cooling and Heating Perception

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Abstract. A series of experiments have been conducted to evaluate human thermal response to asymmetric thermal stimulation. It has been validated in previous studies that asymmetric thermal stimuli can create perceptions of heating or cooling while maintaining a constant average temperature applied to the skin. In this study we implemented three experimental procedures on the ventral forearm to evaluate asymmetric thermal stimulation. These experiments also examined several ways to collect perceptual thermal responses from subjects. Constant and average temperatures were adjusted based on multiple aspects of thermal perception theories. Temporally optimized thermal patterns were implemented and resulted in counter-intuitive thermal perceptions. These results also demonstrated that the perceptual neutral point differs from the thermally neutral point on the skin.

1 INTRODUCTION

Human skin contains thermal sensors that react to temperature changes. The perception of temperature is non-linearly related to the rate of temperature change; faster changes in temperature are noticed more quickly. This study evaluates how multi-channel dynamic temperature inputs can affect the perception of temperature without changing the average temperature of the skin. This is done by using the non-linearity in perception of temperature. By arranging a grid of independently controlled temperature actuators, one actuator can always be heating/cooling quickly while the others are cooling/heating slowly as shown in Figure 1. Alternating which actuator is changing temperature quickly ensures that the average skin temperature never changes while the person will perceive that their skin is constantly heating or cooling. This method has been demonstrated to be effective for cooling [1] and heating [2]. The purpose of this work is to examine how to better evaluate the perception of temperature and evaluate an optimized thermal pattern without adjusting skin temperature prior to the experiment. This study also differs from previous ones in that the location of stimulation is the ventral forearm.

2 BACKGROUND

The thermal aspects of haptic feedback have not been studied as richly as other areas of haptics. Existing obstacles for thermal feedback delivery include slow

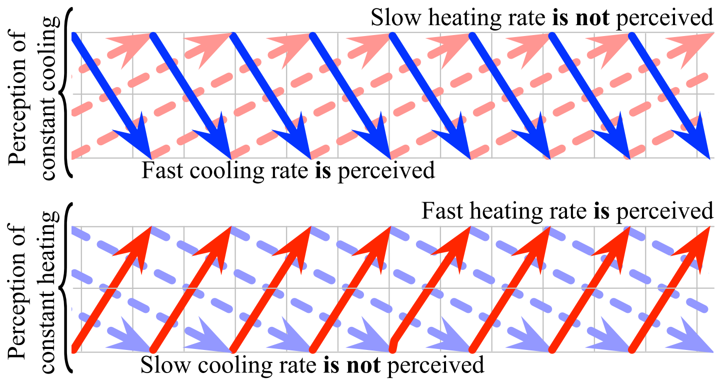


Fig. 1: This figure illustrates the presented concept: quickly changing temperatures are noticed more quickly than slowly changing temperatures. This can be completed be either making the faster (i.e., more noticeable) direction of temperature change be either increasing or decreasing.

response of current thermal devices and high power consumption, which has restricted their use in a portable set up. Another restricting consideration is that multiple environmental variables can affect thermal perception.

Information related to temperature is processed in the cerebral cortex [3]. Thermal receptors for measuring hot and cold are specific and utilize distinct mechanisms to detect temperature variation on the skin [4]. These two receptors have different conduction velocities. Cold receptor conduction velocity is ten times faster than warm receptors [5]. The distribution of cold and warm receptors on the skin varies drastically; cold receptors outnumber warm receptors with a ratio of 30:1 [6]. Hot and cold receptors are both active between 30°C and 36°C [7]. Green [8] found that pain receptors are activated when temperature exceeds 45°C or is below 18°C. Thermal perception can be attributed to the rate of temperature change, magnitude of change, body temperature, and location of stimulation [9]. Although temperature perception depends on various factors, the primary contributor is considered to be the rate of temperature change [10]. Based on a psychophysical experiment by Molinari et al. [11], thermal sensitivity shows a non-linear behavior; a greater variation in temperature is required at low temperature change rates to activate thermal receptors.

Incorporating thermal feedback into existing virtual reality systems can create an even more immersive VR environment. It has been shown that thermal cues can affect haptic perception; for example, the temperature-weight illusion [12]. Several researchers have attempted to include thermal feedback into tactile haptic devices [13–15]. Ho and Jones [16] were able to simulate thermal properties for virtual objects. In their experiment subjects identified virtual object materials without visual feedback. In a series of studies, Peiris focused on employing thermal devices on the forehead for perception evaluation and virtual reality applications [17–19].

The area of thermal stimulation can be related to thermal sensitivity. Since there is not a thermoreceptor on every point of the skin, thermal summation occurs [20]. Thermal summation is the perception of the average temperature of actuated thermal stimuli over a certain area of the skin. Thermal stimulation area is inversely related to the thermal threshold. Therefore, by changing the stimulation area, the thermal threshold can change.

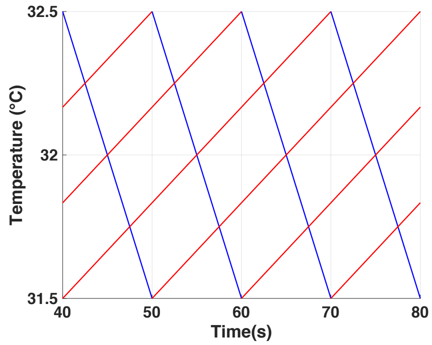
Synthetic heat can be referred to as a thermal illusion occurring when adjacent thermal receptors on the skin are receiving different thermal information [21]. Confusion in interpretation of sensory information leads to temporary sensation of pain. A similar effect is the thermal grill illusion [22]. It should be noted that the mechanism by which these two sensations are created is distinct although they both typically create an excessive heat sensation. Our goal in this research differs from synthetic heat and the thermal grill illusion in that we aim to create thermal perceptions using asymmetrically changing temperature rates while avoiding the painfully hot feelings induced from these thermal illusions.

Manasrah et al. [1] employed a dynamic thermal pattern where they created a perception of constant cooling on the skin without changing the overall average temperature of the skin. One of the patterns used by Manasrah et al. [1] sequentially increased/decreased the temperature of the actuators in order, across the forearm, so that each location felt a delayed version of the adjacent actuator. In these 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 10 seconds, the rapidly changing actuator changes its direction to a slowly changing rate and every 30 seconds the slowly changing actuators switch direction which creates a 30/10 temporal pattern similar to that shown in Figure 2a. The mechanical equivalent of such perception can be induced by applying asymmetric oscillating forces where a subject feels that a constant force is applied in one direction without applying any net force [23]. By reversing heating and cooling a constant heating perception was created in the same fashion [2].

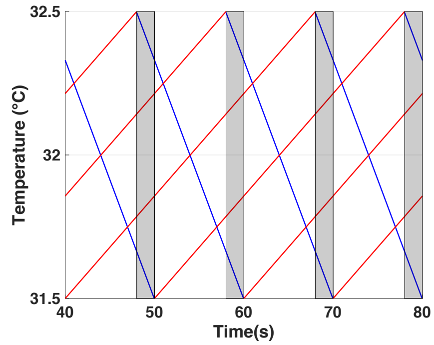
3 Methodology

3.1 Experimental Theory

Under the standard pattern for generating a perception of constant cooling or heating, as described above, the first actuator segment is at its initial value as the second actuator segment reaches its peak value. However, this is not likely the most efficient pattern because it takes some time to cross the threshold of feeling a temperature. Ideally, the actuator that is changing direction would pass the thermal perceptual threshold at the same time that the quickly changing actuator switches to slowly changing temperature. By creating a thermal pattern in which fast changing temperatures overlap, we hypothesize that a stronger thermal perception can be created. To achieve the desired overlap of actuators, the required time pattern becomes 28/12 heating/cooling with a ten second delay between actuators as shown in Figure 2b. These patterns are thought to improve thermal stimuli by increasing the fast heating/cooling time of thermal stimulation to create a more pronounced perception.



(a) Normal asymmetric pattern



(b) Overlapping asymmetric pattern

Fig. 2: Comparison of (a) normal and (b) overlapping constant cooling asymmetric thermal pattern. Each line corresponds to one actuator. Red lines are slowly heating and blue lines are rapidly cooling.

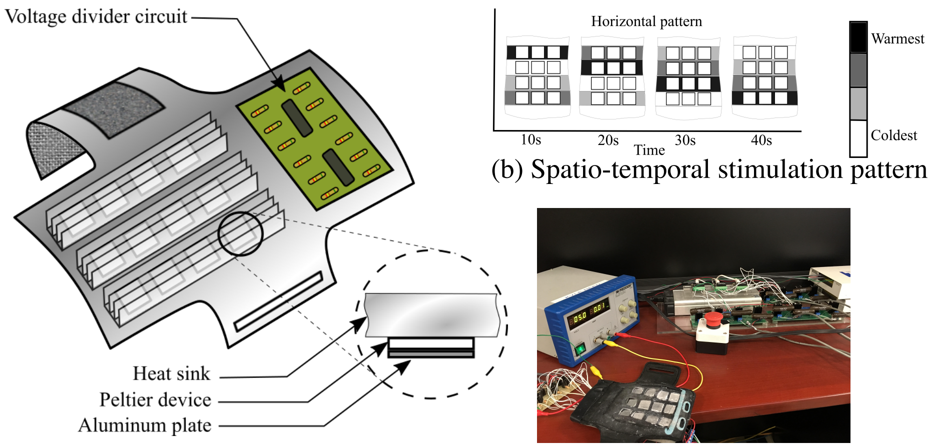
3.2 Experimental Device

We used thermoelectric (Peltier) devices to test our theory of overlapping quick temperature changing actuators. Peltier devices convert electric current to a temperature gradient. These devices can perform both as coolers and heaters depending on the applied voltage polarity as long as one side is kept at a relatively constant temperature. This device allows us to investigate asymmetric thermal stimulation on thermal perception of the glabrous ventral forearm. Furthermore, we will implement new thermal patterns which are hypothesized to improve efficiency of thermal stimuli patterns called overlapping heating/cooling patterns.

The thermal device built to test our hypothesis consists of 12 equally spaced thermoelectric actuators (peltier devices). Each peltier is 14.8mm x 4.8mm x 3.6mm which creates a total actuation area of 48.5cm^2. Every thermal cell was actuated and controlled independently with closed loop feedback using an NTC 10K ohm thermistor. Each thermistor was placed inside an aluminum plate (15mm x 15mm x 3mm) to record the temperatures more precisely. The plates were attached to the peltiers using thermal paste. Since one side of each peltier had to maintain a constant temperature, three heat sinks were mounted on the back of the device to dissipate the generated heat (see figure 3). Each heat sink (98mm x 20mm) covered four peltiers. The device was strapped to the subject's arm to ensure full contact with their skin. The peltier voltages were regulated via three PhidgetAnalog-4 output boards. Each board can control four thermal cells independently, so all twelve were independently controlled. Control of the twelve peltier plates was carried out in LabVIEW. PID controllers were implemented to drive the thermal actuators to the desired temperatures.

3.3 Experimental Procedure

Three sets of experiments were conducted to test several aspects of portraying a perception of heating or cooling without actually changing the average tem-



(a) Experimental setup schematic (b) Spatio-temporal stimulation pattern (c) Experimental setup and circuitry

Fig. 3: Experimental setup schematic and stimulation pattern.

perature. By keeping the average temperature constant, cooling or heating perception can be created continuously without exceeding the skin's neutral temperature zone. An experimental set involves a combination of constant temperatures and heating/cooling thermal stimuli. The following conventions will be used throughout this manuscript: base temperature stimulation will be referred to as constant, asymmetric heating/cooling patterns will be simply referred as heating/cooling, and overlapping asymmetric heating/cooling patterns will be referred as overlapping heating/cooling.

Participants were seated on a chair inside a temperature controlled room with an ambient temperature of 23°C. Prior to the experiment, subjects were asked about their handedness and age. Participants' skin temperatures was measured on the same location of stimulation using a Nubee 8380 non-contact infrared thermometer. After participants were given a brief explanation of the experiments, they placed the ventral side of their forearm on the device and a strap was attached to hold it in place. During the experiment, they were asked to describe their thermal sensation on the forearm using the American Society of Heating, Refrigeration, Air conditioning Engineering (ASHRAE) thermal sensation scale. The scale consists of seven thermal levels: hot, warm, slightly warm, neutral, slightly cool, cool, and cold from +3 to -3, respectively. Participants had to remove their arm from the device after each experiment to avoid exposure to rapid temperature changes that were created before the thermal pattern goes into effect as well as avoiding the thermal grill illusion. Subjects were asked to ignore the first 10 seconds of the experiment so that their arm and device temperature could reach an equilibrium. Once the ten seconds was over, they were asked to report their initial perception.

During the three different experimental sets, voluntarily and involuntarily responses were collected from participants. Involuntarily responses were those asked at certain intervals. Participants were also instructed to report any changes in their thermal perception between those intervals; these were considered to be voluntarily reporting of temperature perception. Each subject's perception rate is considered to be the average of his/her voluntarily and involuntarily responses during the experiment. Each of the three experiments included different intervals for involuntarily response. In the first experimental set, subjects were asked three times about their thermal perception in 20-second intervals. In the second experimental set, subjects were asked six times with intervals of 20 seconds. This time increase was to observe the effect of habituation on their thermal perception with asymmetrically changing temperatures. On the third experimental set, the subjects were asked at the 40th, 70th, and 100th seconds for the base pattern; for normal cooling/heating patterns times were at the 47th, 70th, and 102nd seconds of the pattern. Those time for overlapping patterns were at the 54th, 80th, and 112nd seconds of the pattern. These different times were specified to avoid the periods of transition, so the responses would be more representative of the majority of the perception they felt.

Each experimental set was aimed at identifying the following specific aspects of asymmetric thermal stimulation:

1. **Experimental set 1:** Heating and cooling patterns were implemented at three temperatures. Skin temperature can be considered to be approximately 31°C [24]. Accordingly, the experiments were performed at 30°C, 31°C, and 32°C, just below, at, and just above skin temperature . Nine patterns were investigated in total; base patterns at 30°C, 31°C, and 32°C, heating at 30°C and 31°C, cooling at 31°C and 32°C as well as overlapping cooling and heating at 31°C. The reason to choose 31°C for overlapping pattern was that it is the midpoint of three temperatures so any biases in interpretation of the results is avoided.
2. **Experimental set 2:** Body temperature is subjected to change depending on metabolism, activity, ambient temperature, gender and feeling [25]. Since the effect of taking participants' local body temperature to a certain point had already been investigated, an alternative approach was chosen in this study to evaluate the results. Based on observations from subjects in experimental set 1 and, due to variations in skin temperature, we decided to choose stimulation temperatures based on subjects' skin temperature. Similar to experimental set 1, there were nine patterns in total including: three base temperatures and 1°C above and below skin temperature, heating and cooling patterns at skin temperature as well as heating at -1°C and cooling at +1°C skin temperatures. Overlapping heating and cooling at skin temperature were also evaluated. The reason for choosing these patterns was to observe the correlation between pattern average temperature and the effectiveness of the stimuli.
3. **Experimental set 3:** The first two sets of experiments indicated that skin temperature is not a reliable set point for the neutral point, since most subjects perceived a temperature equal to their skin temperature as warm. As a result, subjects were asked about their perceptual neutral point which is not necessarily their skin temperature. It has also been regarded that there is a thermally neutral region rather than a thermally neutral point on the

skin [4]. Consequently, the method of limits was implemented to identify the neutral region prior to the main experiment. Once the cool/warm points were identified, ascending/descending patterns at a rate of 0.03°C/sec were played on participants' skin until they reported a neutral perception. The neutral point was assumed to be the average of the two border values. Since the range of the neutral point for most of the subjects was more than 2°C, average temperatures were chosen as ±1.5°C of the neutral point. In this experimental set, we investigated eight thermal patterns as the following; two base temperatures at ±1.5°C, overlapping cooling pattern at -1.5°C, cooling at ±1.5°C, heating at ±1.5°C, and overlapping heating at +1.5°C of neutral point.

3.4 Subjects

Eighteen participants (7 females and 11 males) participated in all experiments in total. They were all healthy, aged between 18 and 34. Twelve subjects participated in experimental set 1, nine subjects participated in experimental set 2, and nine subjects participates in experimental set 3. Each read and signed a consent form before commencing the experiment. The experiment followed a protocol approved by the University of South Florida's Institutional Review Board.

4 Results

A one-way repeated measures ANOVA test was conducted on data from each experiment. Each test had an independent variable of baseline temperature. Sphericity was evaluated for each experiment using Mauchly's test for sphericity and corrections using Greenhouse-Geisser estimates of sphericity were applied where sphericity had been violated. When statistical significance was found, a post-hoc test was performed with Bonferroni corrections. All statistical tests were based on an alpha value of 0.05 using SPSS. In forthcoming figures *constant* refers to holding all the thermal actuators at a constant temperature and *Heating/Cooling* refers to the asymmetric heating/cooling rates. An asterisk on top of the bars indicates significant difference of each two patterns. One asterisk indicates a p-value<0.05, two asterisks indicate a p-value<0.01, and three asterisks indicate a p-value<0.001. In the following figures green bars represent the constant thermal patterns, blue bars represent cooling patterns and red ones correspond to heating pattern stimulation.

Figure 4 shows the mean, standard error, and statistical significance of experimental set 1 results. The repeated measures ANOVA test showed a significant difference between thermal patterns ($F(8, 88)= 8.748$, $p<0.001$). There is no statistically significant difference between constant 30°C, 31°C, and 32°C nor the same temperatures with a pattern applied. Perception of constant temperatures increased proportionally while, stimuli patterns created inconsistent perceptions. Heating at 30°C resulted in the coolest perception among all having a mean perception rate of -1.19. Cooling at 32°C also resulted in a warm perception although it was still warmer than the constant counterpart. We call

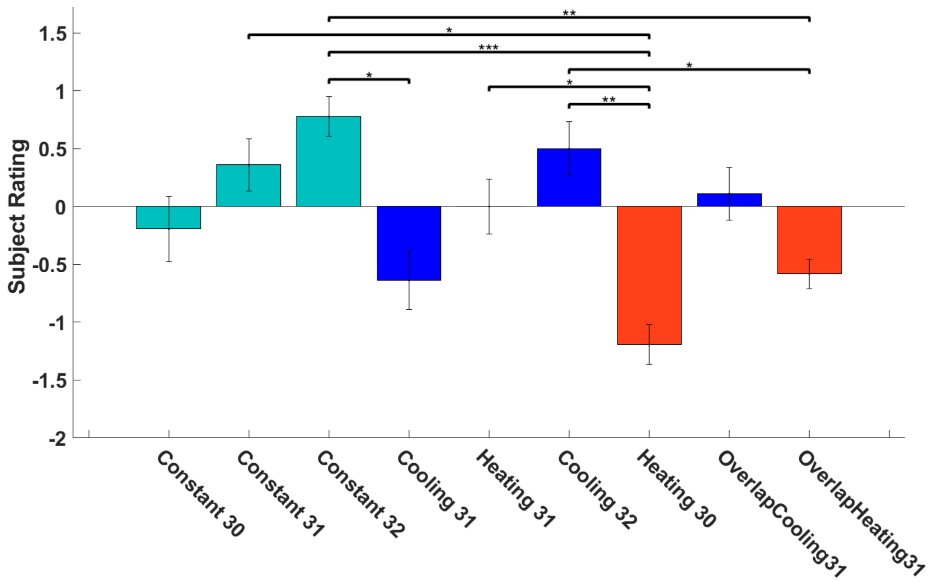


Fig. 4: Experimental set 1 results evaluating thermal stimuli based on fixed base temperatures.

these two patterns counterintuitive since they resulted in opposite perceptions. We can relate this effect to the spatial-temporal aspect of thermal perception; stimulation below threshold can be perceived more dominantly if applied over a large area of the skin compared to stimuli with higher intensity at smaller areas. Greater difference of cooling perception compared to heating perception in counterintuitive patterns can be related to the fact that warm thermoreceptors are activated at a higher heat exchange rate than cold threshold, so a greater area is required to create a similar perception intensity. Heating at 30°C created a more intense perception compared to constant 30°C. We hypothesize this can be caused by the presence of the rapidly increasing pattern; cold is perceived stronger in neighboring of increasing patterns rather than similar thermal patterns. Heating at 31°C was statistically warmer than heating at 30°C which is likely because the average temperature is not low enough to activate spatial-temporal effect. Counterintuitive perception is diminished in overlapping cooling and heating likely due to longer duration of rapidly cooling and heating.

In the second set of experiments, Mauchly's test indicated that the assumption of sphericity had been violated for this experimental set ($\chi(1)^2 = 58.37$, $p<0.05$), and the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\epsilon = 0.54$). ANOVA test resulted in a significant difference between thermal patterns ($F(84.33,\ 34.69) = 6.86$, $p<0.001$). All patterns except for heating at skin temperature were warmer than experimental set 1. This is in agreement with our expectations since the average body temperature of subjects was 32.5°C, which elevates all pattern average temperatures by 1.5°C. Figure 5 shows a similar incremental increase in perception in constant

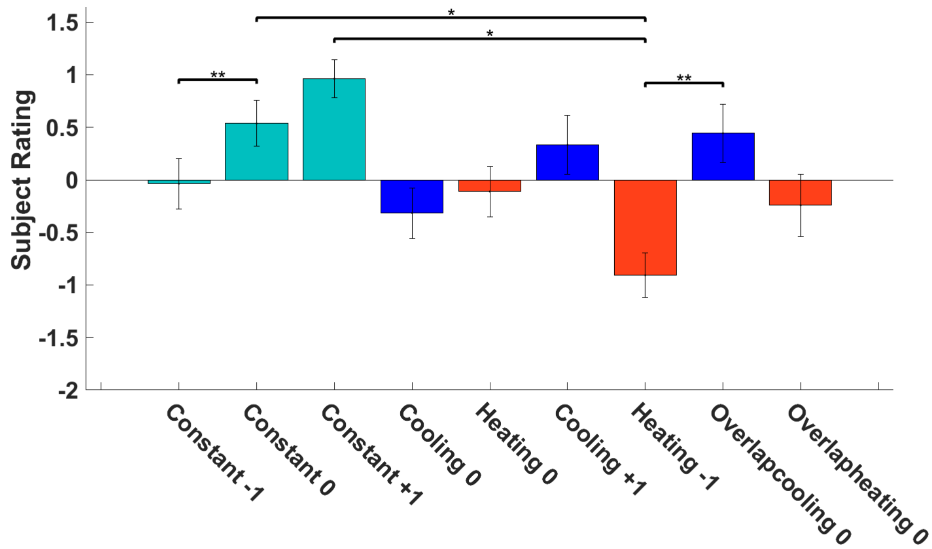


Fig. 5: Experimental set 2 results evaluating thermal stimuli based on skin temperature.

temperatures with a significant difference between base 0°C and -1°C. Elevation of average temperature diminished effect of spatial-temporal effect on heating at -1°C and cooling at +1°C of skin temperature.

Figure 6 illustrates the collected results from experimental set 3. Mauchly's test indicated that the assumption of sphericity had been violated for this experimental set ($\chi(1)^2$= 46.83, $p<0.05$), and the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ϵ= 0.45). ANOVA analysis showed a statistically significant difference between thermal patterns (F (3.171, 25.37) = 16.19, $p<0.001$). It can be noticed that all thermal patterns at -1.5°C were perceived distinctly cooler than their counterparts at +1.5°C. In the post-hoc test, statistical significance was observed between heating at +1.5°C and -1.5°C. This difference highlights the relation of the spatial-temporal effect to the average temperature. For some subjects, the neutral region range was more than 3°C, which could be a contributor for less sensitivity to thermal stimulation. A paired-samples t-test was conducted to compare participants' skin temperature and their perceptual neutral point. A t-test was performed since there were only two parameters to be compared. Analysis resulted in a significant difference between the skin temperature (M=32.25, SD=1.14) and perceptual neutral point temperature (M=30.07, SD=1.45); t(6)=8.34, $p<0.001$). This finding can justify the rationale of experimental set 3 which aimed to understand the differentiation between skin temperature and the perceptual neutral point.

5 DISCUSSION

Consistent trends can be observed between experimental sets. Constant temperatures in experimental set 2 created a generally warmer perception than

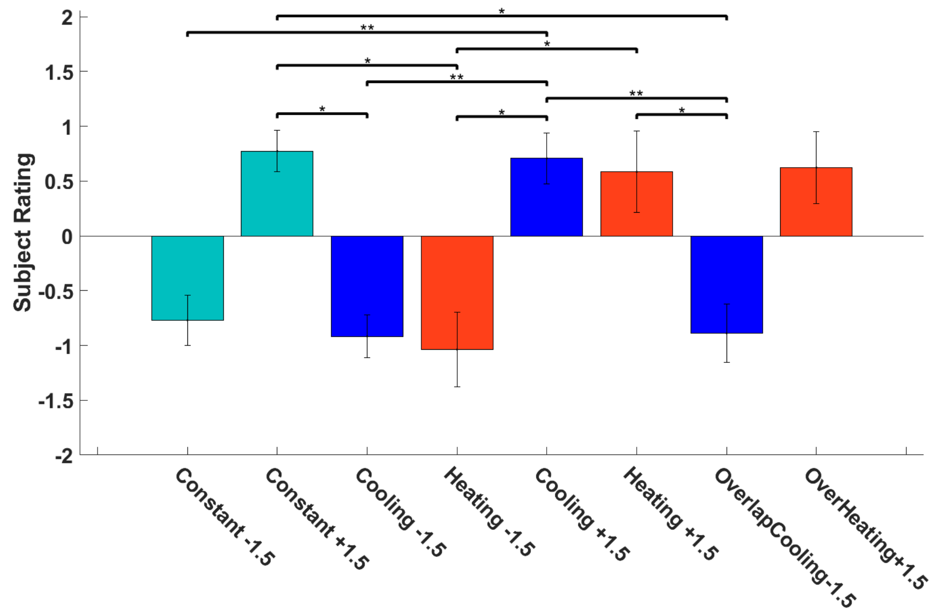


Fig. 6: Experimental set 3 results evaluating thermal stimuli based on perceptual neutral point.

the corresponding pattern on experimental set 1, and constant temperatures in experimental set 3 had the highest perceptual difference which was evident due to higher temperature difference. Heating stimuli created a counter-intuitive cooling effect on skin which decreased by increasing the average temperature. This is attributed to the spatial-temporal aspects of thermal perception. We hypothesize that creation of more pronounced perceptions is likely due to the fact that at low temperatures slowly cooling patterns were close to the threshold of cold thermoreceptors as well as being projected to a larger area of the skin compared to rapidly heating pattern. Another reason for effectiveness of cooling patterns can be more abundance of cold thermoreceptors on the skin compared to warm ones [6]. However the same effects were not observed in overlapping heating patterns due to higher thermal thresholds for heat.

Thermal patterns on each experimental set were selected based on various rationale taking into account the effect of average temperature on thermal stimuli, remaining in the neutral thermal zone, number of active fast changing actuators, and experiment duration. We hypothesize that changing the experiment location to the glabrous skin contributed to the variation of the results. Since the ventral side of the arm is closer to the veins carrying warm blood, they can be considered as a heat source while dorsal side of the arm is more insulated from veins by the flexor muscles.

A difficulty during the experiment was to devise a widely-acceptable perceptual definition for each perception level. Verbal definition of thermal perceptions can be interpreted differently. Moreover, there is no way to assign a defined temperature corresponding to each perceptual point because of skin temperature variations on each subject.

6 Conclusion

A new approach to asymmetric thermal stimulation was taken to investigate the effectiveness of various thermal stimulation patterns on a new location of the forearm compared to previous studies on asymmetric thermal stimulation. Effectiveness of optimized thermal patterns with longer exposure of skin to rapidly changing temperatures were evaluated as the initial motivation of this study. The proposed patterns resulted in a counterintuitive effect where asymmetric heating created a cold perception. Later thermal perception issues instigated fundamental questions regarding the perceptual thermally neutral point which we pursued in the rest of this study. Existence of slowly cooling and rapidly heating patterns resulted in a magnified perception of cold without creating the thermal grill sensation. Considerable perceptual differences were observed between dorsal and ventral areas of the arm which can partially be attributed to whether the skin is glabrous or hairy. It was evaluated that objects at skin temperature are perceived statistically warmer. In future studies experiments should be implemented to utilize spatial-temporal aspect of thermal stimulation to create more pronounced desirable thermal perceptions.

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