2017 IEEE World Haptics Conference (WHC)
Fürstenfeldbruck (Munich), Germany
6–9 June 2017

Asymmetrically-Applied Hot and Cold Stimuli Gives Perception of Constant Heat

Ahmad Manasrah[1], Nathan Crane[2], Rasim Guldiken[2], Kyle B. Reed[2]

***Abstract*— This study investigated how the perception of skin temperature is affected by asymmetrically changing hot and cold stimuli applied to nearby sections of the skin. In the first part of the study, different rates and starting temperatures were applied to evaluate the time at which the temperature change was first noticed. In the second part, a method of asymmetrically-applied hot and cold stimuli was tested on the participants to generate a constant heating sensation without changing the average temperature of the skin. This method applies a combination of fast heating and slow cooling rates using multiple thermal actuators. The slow cooling rate is under the perceptual threshold level, hence it is not perceived. The fast heating rate, however, is perceived, which creates the feeling that the temperature is warmer than it actually is. The results showed that participants were able to perceive a constant heating effect at normal skin temperature as hypothesized. This effect was most effective at normal skin temperatures and became less effective at higher baseline temperatures.**

I. Introduction

Thermal displays have the potential to be incorporated into haptic interfaces and virtual environment simulations. The feedback of thermal displays is used to convey information about the thermal properties of a remote or a virtual object. For example, Ho and Jones found that thermal cues can help identify objects when visual feedback is limited [1]. However, thermal perception is relatively slow compared to tactile perception, which generally makes the incorporation of thermal displays less common in haptic applications. This balance between the benefits and limitations of thermal displays makes it important to study and investigate them.

There are different receptors that measure hot and cold in the skin, and their perception is mainly dependent on the rate of temperature change [2]. Since slower rates of change cause a nonlinear increase in warm and cold thresholds [3], we hypothesize that applying dynamic thermal inputs on the skin will trigger unique thermal display capabilities. In a grid of independently controlled thermal actuators, one or more actuators can always be heating quickly while others are cooling slowly as shown in Figure 1. Changing the actuators between quickly heating and slowly cooling ensures that the average skin temperature remains unchanged, but due to the nonlinear characteristics of temperature perception, the person will perceive that their skin is continuously warm. The concept of this method is somewhat similar to generating a perception of force applied in a single direction by using an asymmetrically applied oscillating force where the net applied force remains unchanged [4]. We have previously demonstrated a similar effect of constant cooling with the heating and cooling patterns inverted [5].

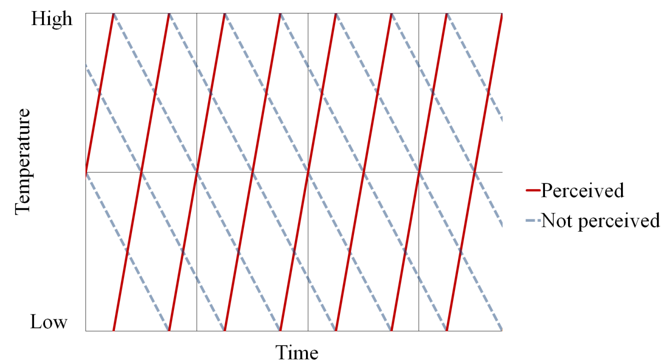

Fig. 1. Slowly cooling actuators (dashed lines) mixed with quickly heating actuators create the feeling of constant heating.

The aim of this research is to investigate our hypothesis using multiple dynamic localized thermal inputs and to study the thresholds of hot and cold receptors using different heating and cooling rates of change and baseline skin temperatures. The results of this study will increase our understanding of thermal perception and will provide new information about the temperature thresholds of relatively slow rates of change.

II. Background on Thermal Perception

Human skin has the ability to detect changes in the temperature depending on two main types of thermal receptors: cold receptors, which respond to decreases of temperature between 5°C and 45°C, and warm receptors, which respond to temperature increases up to 45°C [6]. Typically, human skin contains more cold receptors than warm receptors by as much as 30:1 [6][7]. Thermal sensations can be perceived when skin temperature is between 13°C and 45°C [7]. Pain sensation is evoked if skin temperature is below or above this range [8].

Temperature perception depends on many factors including: the rate of temperature change, baseline temperature of the skin, the location on the skin, and the amplitude of temperature change [9]. Hensel [10] stated that the rate of change, the skin area of stimulation, and the skin's temperature affect the thermal sensitivity of the skin. The sensitivity of the skin is measured by the threshold at which the stimulus is first perceptible. For instance, the skin on the

[1]Manasrah is in the Department of Mechanical Engineering at Al-Zaytoonah University, Amman 11733 Jordan.
ahmad.mansrah@zuj.edu.jo
[2]Crane, Guldiken, and Reed are in the Department of Mechanical Engineering at the University of South Florida, Tampa, FL, 33620.
[guldiken, nbcrane, kylereed]@usf.edu

978-1-5090-1424-8/17/$31.00 ©2017 IEEE

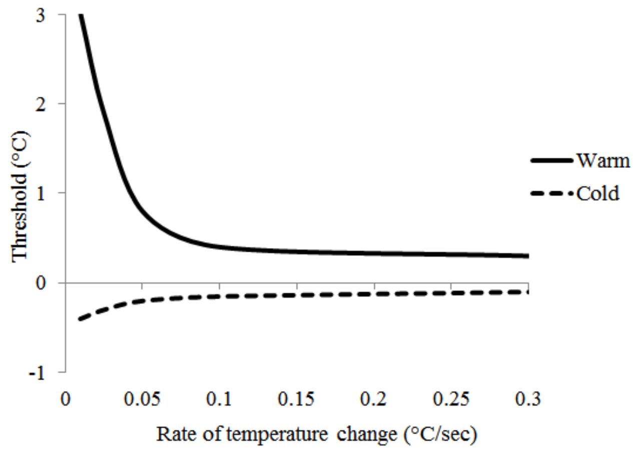

Fig. 2. The rate of change affects the thresholds at which temperature changes are first noticed. Figure is recreated based on the data from [3].

palm of the hand can detect a temperature increase of 0.2°C (at a rate of 2.1°C/s) when starting at 33°C [11]. However, for smaller rates of change, an observer will not be able to detect a change in temperature until it has increased by 5–6°C [6][9]. Increasing the rate of change above 0.1°C/s has little effect on the temperature threshold [12][13]. Figure 2 shows the nonlinear relation between thermal threshold and the rate of temperature change.

The thermal threshold is inversely related to the area of thermal stimulation. The poor spatial resolution of thermal stimuli is due to spatial summation. Spatial summation occurs when the sensed temperature is based on the spatial average of thermal stimuli over an area or feature of the body [14]. Changing the shape or area of stimulation can change the threshold of thermal perception. As the area of a warm stimulus increases, the threshold becomes noticeably lower [12]. The contribution of area of stimulation to warm sensation becomes less significant as the intensity increases [14], whereas to cold, the contribution of area remains fixed as the intensity increases [15].

Although the spatial resolution of nearby temperature differences is poor, it has been shown that large temperature differences between a stimulus and nearby skin areas can create a confusion in thermal perception [16], and it often happens when adjacent hot and cold sensors perceive a discrepancy. This phenomena is referred to as synthetic heat [17] and was first discovered by Thunberg [18][19] who called it the thermal grill illusion. Although the outcome of both terms is perceiving excessive heat sensation, synthetic heat usually refers to applying equal amounts of heating and cooling on two locations on the skin, whereas thermal grill refers to heating and cooling in an alternating sequence. The effects of synthetic heat and thermal grill illusion are often accompanied with the momentary sensation of pain.

The idea behind the method presented here is to generate a continuously warm sensation on the skin that is distinctly different than the synthetic heat and thermal grill illusion. In this method, the temperatures of the actuators are constantly changing with two different rates for cooling and heating unlike the thermal grill illusion where each actuator has a constant temperature and does not change direction between heating and cooling. Additionally, only 1°C temperature difference is applied between the heating and cooling stimuli in this method whereas the temperature difference can get up to 20°C between the heating and cooling stimuli in the thermal grill illusion [19].

III. Method

This study was divided into two experimental parts: (1) thermal thresholds and (2) constant heating perception. The first part investigated the perceptual threshold of a decreasing temperature from three baseline starting temperatures using three rates of change, focusing on the length of time to perceive the change. The second part studied the effect of applying asymmetric hot and cold stimuli using two average operating temperatures. The two parts of the study were conducted on the dorsal area of the dominant forearm using the same apparatus and subjects.

A. Apparatus

The experiments were conducted using a twelve-channel thermal stimulation device. The thermal stimulation was created using peltier devices [20], each with the dimension of 14.8 mm x 14.8 mm x 3.6 mm, to create a 4 x 3 grid. With a 7.5 mm space between the actuators, the total area of stimuli was 48.53 cm^2. The ability of Peltier coolers to convert electric current to temperature enables us to build an easily-controlled temperature display with no mechanical or moving parts. Each actuator was independently controlled using the temperature feedback from a thermistor. To provide an accurate temperature reading, each thermistor was inserted into an aluminum plate (15 mm x 15 mm x 3 mm) that was attached to the surface of the Peltier device using thermal paste, as shown in Figure 3. Three heat sinks (98 mm x 20 mm) were mounted on groups of four actuators

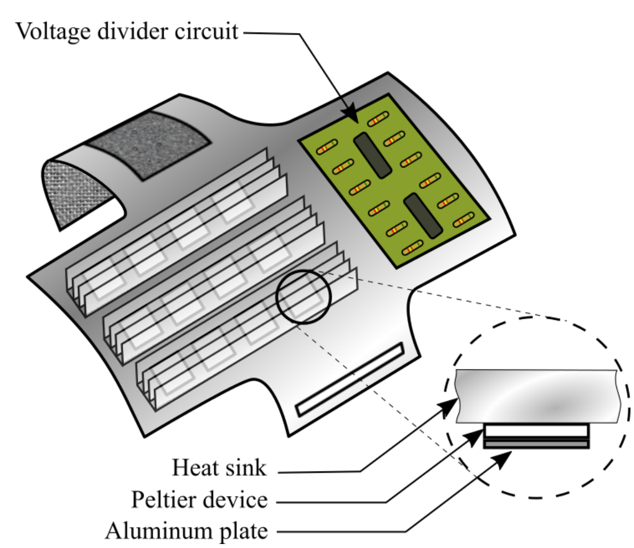

Fig. 3. A sketch showing the parts that were used in the twelve-channel thermal stimulation device.

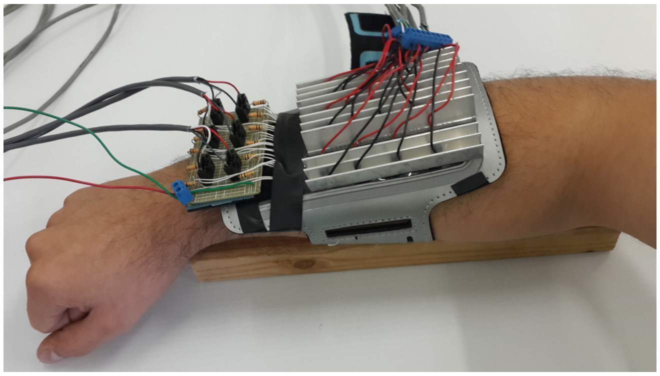

Fig. 4. The device used in the experiments is strapped on the forearm to test both temperature thresholds and the constantly changing thermal pattern on humans.

to dissipate heat. The device was strapped to the forearm to ensure full contact between the actuators and the skin, as illustrated in Figure 4. For the safety of the participants, proper caution was taken to avoid any electrical contact or excessive temperatures.

A proportional feedback controller was used to drive the thermal actuators. The controller calculated the required temperature and output a voltage to the operational amplifiers that were in a voltage-controlled current source configuration. These sent current to the Peltier devices, which could increase or decrease the surface temperature of the aluminum plates touching the skin.

B. Thermal Threshold

The first part of the study tested three rates of cooling (0.05°C/s, 0.033°C/s, and 0.022°C/s). These rates were chosen to test our hypothesis of creating a unique thermal display and to examine how participants react to the temperature change. Also, there is little research that has been done studying thermal thresholds on such low rates of temperature change. Three baseline starting temperatures were used (29°C, 31°C, and 33°C) with the rates of temperature change making a total of nine conditions. Our experimental procedure is different than a typical threshold experiment since we wanted to evaluate the perception of some actuators changing when others were not, which is similar to the continuous heating method described in Figure 1. As such, only three actuators out of the twelve were cooling while the other nine remained at the baseline temperature. Figure 5(a) shows the layout of the actuators where three are cooling diagonally and the rest are at a constant temperature. The total surface area of thermal stimulation was approximately $7\,\text{cm}^2$. Figure 5(b) illustrates the difference between the three rates of temperature change over a 60 second period.

C. Multiple Thermal Stimuli

The second part of the study used twelve actuators to investigate the concept of perceived constant heating. The twelve actuators were put into four groups of three.

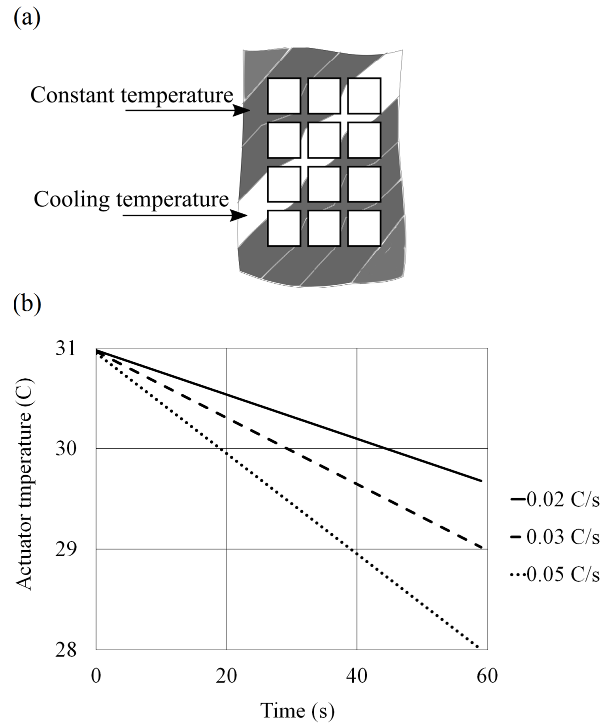

Fig. 5. (a) The layout of the activated actuators. (b) The rates of change that are used in the first part of the experiment for a 31°C starting temperature.

Three groups of actuators were slowly cooling at a rate of 0.033°C/s over 30 seconds with each group out of phase from each other while one group was quickly heating over ten seconds at a rate of 0.1°C/s. Every ten seconds, the actuators that were heating would start slowly cooling down and another group would start quickly heating. Two different average temperatures (31°C and 33°C) were used with the diagonal pattern applied on the forearm. Figure 6 shows the thermal pattern of the continuous heating method. In addition, two control conditions maintained constant temperatures of 31°C and 33°C as a neutral temperature reference point for comparison. In all cases, even though the temperature linearly changed within 1°C difference, the average surface temperature of the skin did not change during the trials. Before generating the pattern, all actuators were slowly warmed up to match their corresponding average temperature for the trial.

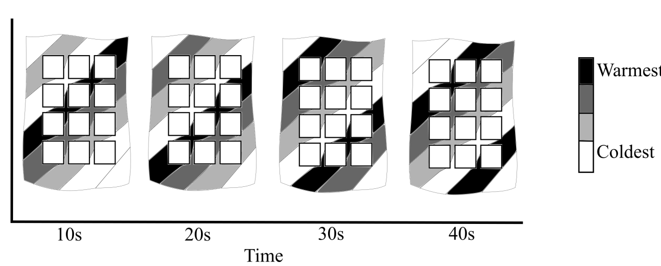

Fig. 6. Heating and cooling patterns used in the second experimental set.

D. Procedure and Participants

Ten participants (eight males and two females) participated in this study. They were all healthy and between 18 and 55 years old. Nine of the participants were right handed. Each participant read and signed a consent form before commencing in the experiment that followed a protocol approved by the University of South Florida's Institutional Review Board.

Participants were seated in a chair inside a temperature-controlled room with an ambient temperature of 23°C. After the participants were given a brief explanation of the experiments, their forearm temperature was measured. Their skin temperature ranged between 30°C and 32°C on the dorsal area of the dominant forearm.

In the first part of the experiment, the cold threshold of different rates of change and baseline starting temperatures was studied (section III.B). After one minute of transition time, to allow the actuators to reach the baseline temperature, three actuators started to cool down according to the assigned rate of change for one minute. Participants were instructed to report when they perceived a clear sensation of cold. Each participant completed nine randomly ordered experiments in this part in an average of 15 minutes.

The second part of the experiment tested the concept of constant heating using twelve actuators (section III.C). Three trials were conducted using two average temperatures (31°C and 33°C) with a cooling rate of 0.033°C/s over 30 seconds and a heating rate of 0.1°C/s over 10 seconds. Two trials applied a constant temperature of 31°C and 33°C, respectively, throughout the trial as a neutral reference for comparison. At the beginning of each experiment, the actuators were given one minute to warm up and settle on the starting temperature. After that, participants were asked to describe their thermal sensation on the forearm every 30 seconds using the American Society of Heating, Refrigeration, Air-conditioning Engineering (ASHRAE) thermal sensation scale [21]. The scale consists of seven thermal levels: hot, warm, slightly warm, neutral, slightly cool, cool, and cold, or from $+3$ to -3 respectively. A two-minute break was given to participants between each experiment.

IV. Results

Two separate repeated measures ANOVA tests were conducted, one on the data from the first part of the experiment (starting temperature and rate of change) and another on the second part (stimuli condition). Mauchly's test of sphericity was evaluated on each of the independent measures and corrections using Greenhouse-Geisser estimates of sphericity were applied if 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.

The first part of the experiment had a dependent variable of response time and two independent variables of baseline starting temperature (29°C, 31°C, and 33°C) and rate of change (0.022°C/s, 0.033°C/s, and 0.05°C/s). The starting temperatures showed a statistically significant effect on the response time ($F(2, 18) = 17.32$, $p < 0.001$). The post-hoc analysis showed that 29°C baseline temperature was perceived statistically significantly faster than 31°C and 33°C. There was no statistical significance between 31°C and 33°C. Figure 7 shows the response times of cooling for the three baseline starting temperatures.

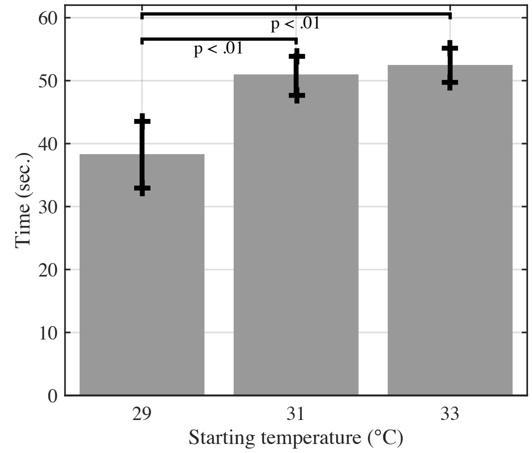

Fig. 7. The results of the response times regarding the baseline starting temperature. The response time to cooling at 29°C is statistically significantly shorter than the response at 31°C and 33°C.

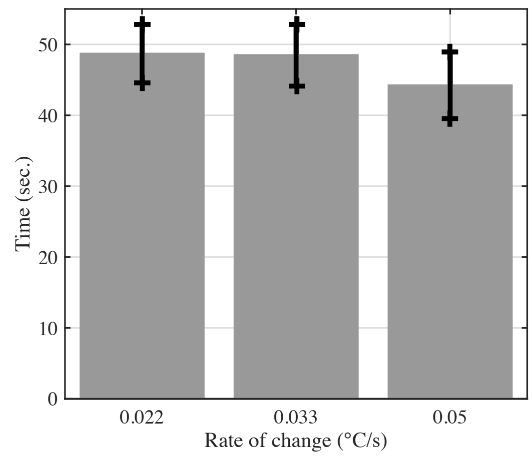

Fig. 8. The results of the response times regarding the rate of temperature change. No statistically significant results were found between the three rates of change.

Mauchly's test indicated that the assumption of sphericity had been violated for the rate of change ($\chi^2(2) = 6.20$, $p < 0.05$), therefore the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\epsilon = 0.65$). There was no statistically significant difference between the rates of change ($F(1.30, 11.70) = 1.55$, $p = 0.25$). The mean response times for all rates of change were longer than 40 seconds, which accounts for a threshold above 1°C with the 0.033°C/s and 0.05°C/s rates of change. Figure 8 represents the response times to cooling at the three rates of change.

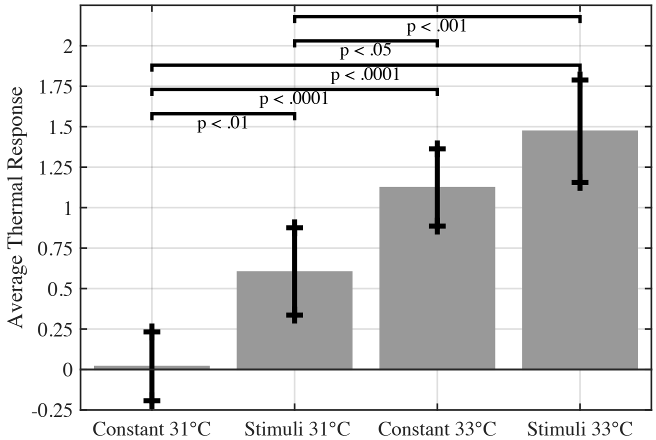

Fig. 9. The results of applying three asymmetric hot and cold stimuli and two constant temperatures at 31°C and 33°C on the last five subjects. No significant results were found between the constant experiments at 33°C and thermal stimulus at the same temperature.

The second part of the experiment had a dependent variable of subjective temperature rating and two independent variables of stimuli condition (constant 31°C, stimuli 31°C, constant 33°C, and stimuli 33°C) and trial (asked seven times at 30 second intervals). The *constant* refers to holding all the thermal actuators at a constant temperature and *stimuli* refers to applying the asymmetric heating/cooling rates (Figure 1). The stimuli condition showed a statistically significant effect on the subjective rating ($F(3,\,27) = 39.90$, $p < 0.001$). The post-hoc test showed that the average thermal response was statistically significant with the stimuli at an average temperature of 31°C compared to constant at the same temperature where participants reported a "neutral" sensation. Continuous heating was also perceivable with the stimuli at an average temperature of 33°C where the average reported temperature increased and was statistically significantly different than the stimuli at 31°C. The stimuli at an average temperature of 33°C was greater than the subjective rating at a constant temperature of 33°C, but was not statistically significantly. There was not a statistically significant difference between the seven intervals of testing. Figure 9 shows the results of the second part of the experiment.

V. Discussion

In this study, we tested thermal thresholds of cooling in ten participants at three baseline starting temperatures and three rates of change to identify if they would have a chance to perceive the slowly decreasing temperatures. The results showed that participants' response time to cooling from 29°C was statistically significantly shorter than the response of the same cooling rates at 31°C and 33°C. Kenshalo [3] investigated warm and cold thresholds as a function of rate of temperature change and showed that slower rates of change caused a noticeable increase in warm and cold thresholds as shown in Figure 2. Kenshalo's study, however, was conducted using one baseline temperature at 31.5°C and a $14.44\,\text{cm}^2$ thermal stimulator which is approximately twice as large as the stimulation used in this study. This suggests that the slowly cooling actuators would be more likely to be perceived during the constant heating experiments, however the average response time is still longer than that used in the constant heating experiments. As such, it is likely that the perception of constant heating, the second part of the experiment, works due to the carefully chosen temperatures that do not cross the cold thresholds, but do cross the heating thresholds.

This difference in the area of stimulation, compared to the literature, may have caused the relatively long response times reported by participants, which can be translated into thresholds higher than 1°C at 0.033°C/s and 0.05°C/s rates of change. Studies have shown that the thermal threshold is inversely related to the area of stimulation [12]. However, this relation is less distinct for the perception of cold [22][23]. Spatial summation can be further investigated with the twelve-channel thermal stimulation device used in this study. The actuators' layout in this device can produce a combination of different sizes and shapes of thermal stimulation to test warm and cold thresholds on areas between $2\,\text{cm}^2$ and $48.53\,\text{cm}^2$.

The second part of this study investigated the possibility of creating a continuous warm sensation without changing the net temperature on the skin using slowly cooling and quickly heating actuators. The results showed that participants clearly perceived continuous heating using thermal stimulation at an average temperature of 31°C. This sensation appeared to taper off as the average temperature deviated from the normal skin temperature. For example, thermal stimulation at 33°C average temperature generated a continuous feeling of heating, yet the application of constant 33°C temperature also generated a similar effect. Participants reported that both experiments had a thermal sensation between "slightly warm" and "warm" on ASHRAE's thermal scale. The lack of the cold perception within the time frames of the 33°C and 31°C average temperature stimuli is in agreement with the hypothesis that is presented here, but within limits. This result may be related to the response functions of hot and cold receptors. Previous studies showed that the static discharge of warm receptors starts at 30°C [24], while cold receptors' static discharge reaches their peak between 25°C and 30°C [25].

During the thermal stimulation of continuous heating, nine actuators were required to be slowly cooling while three actuators were quickly heating. However, the relatively small area of the heating elements caused the threshold to be higher, which made the heating and cooling rate choices very limited. Moreover, it was found that warm stimuli increases the skin's sensitivity to cold [26]. An opposite thermal effect, that is conceptually similar, is easier to create by applying quickly cooling and slowly heating actuators. The slow heating is under the perceptual threshold, so it will not be perceived, but the fast cooling will be perceived. Hence, a constant cooling sensation is generated. We conducted a series of experiments studying the concept of constant cooling and the results from this separate study showed that a continuous feeling of cooling was clearly perceived at 31°C without causing a net change in the thermal state of the body [5].

Based on the results presented in this study, it appears that there is a range at which the asymmetrically applied hot and cold stimuli are most active. To further investigate this range, these stimuli can be tested using temperatures between 25°C and 35°C and can be later compared to controls of constantly applied stimuli in the same range. The results of these comparisons will create a map of thermal responses at which these stimuli are most and least active. Furthermore, the size of the thermal stimulus also affect thresholds [22][27][28]. To study the effect of area, the asymmetrically applied hot and cold stimuli can be tested in 2 x 2, 2 x 3, and 3 x 3 thermal matrices using the device shown in Figure 4.

VI. Conclusion

In this study, we investigated thermal perception of the skin using multiple dynamic localized thermal inputs. Ten participants participated in the experiments. The first part of the study investigated cooling thresholds of three rates of change from three baseline temperatures. The results showed that response times from the 29°C were statistically significantly shorter than the times from the other baseline starting temperatures. However, there was no significant differences between the other rates of change. In the second part of the study, an asymmetrically-applied thermal display was used to create the sensation of continuous heating without changing the average temperature of the skin. The results showed that participants were able to perceive continuous heating at 31°C and, to a reduced effect, 33°C average temperatures. Further work will include studying the effects of asymmetrically-applied thermal stimuli over a larger temperature range and with different stimulation areas.

References

[1] H. Ho and L. Jones, "Material identification using real and simulated thermal cues," in *Engineering in Medicine and Biology Society, 2004. IEMBS'04. 26th Annual International Conference of the IEEE*, vol. 1. IEEE, 2004, pp. 2462–2465.

[2] D. Yarnitsky and J. L. Ochoa, "Warm and cold specific somatosensory systems," *Brain*, vol. 114, no. 4, pp. 1819–1826, 1991.

[3] D. R. Kenshalo, C. E. Holmes, and P. B. Wood, "Warm and cool thresholds as a function of rate of stimulus temperature change," *Perception & Psychophysics*, vol. 3, no. 2, pp. 81–84, 1968.

[4] T. Amemiya, H. Ando, and T. Maeda, "Virtual force display: Direction guidance using asymmetric acceleration via periodic translational motion," in *Eurohaptics Conference, 2005 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2005. World Haptics 2005. First Joint*. IEEE, 2005, pp. 619–622.

[5] A. Manasrah, N. Crane, R. Guldiken, and K. B. Reed, "Perceived constant cooling using asymmetrically-applied hot and cold stimuli," *IEEE Trans. on Haptics*, vol. 10, no. 1, pp. 75–83, Jan.–Mar. 2017.

[6] J. Stevens, "Thermal sensibility," *The psychology of touch*, pp. 61–90, 1991.

[7] L. Jones, M. Berris, *et al.*, "The psychophysics of temperature perception and thermal-interface design," in *Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2002. HAPTICS 2002. Proceedings. 10th Symposium on*. IEEE, 2002, pp. 137–142.

[8] B. G. Green, "Temperature perception and nociception," *Journal of neurobiology*, vol. 61, no. 1, pp. 13–29, 2004.

[9] L. A. Jones and H.-N. Ho, "Warm or cool, large or small? the challenge of thermal displays," *Haptics, IEEE Transactions on*, vol. 1, no. 1, pp. 53–70, 2008.

[10] H. Hensel, "Die intracutane temperaturbewegung bei einwirkung aèusserer temperaturreize," *Pflüger's Archiv für die gesamte Physiologie des Menschen und der Tiere*, vol. 252, no. 2, pp. 146–164, 1950.

[11] J. C. Stevens and K. K. Choo, "Temperature sensitivity of the body surface over the life span," *Somatosensory & motor research*, vol. 15, no. 1, pp. 13–28, 1998.

[12] D. R. Kenshalo, T. Decker, and A. Hamilton, "Spatial summation on the forehead, forearm, and back produced by radiant and conducted heat." *Journal of comparative and physiological psychology*, vol. 63, no. 3, p. 510, 1967.

[13] D. Kenshalo, "Correlations of temperature sensitivity in man and monkey, a first approximation," *Sensory functions of the skin with special reference to man*, pp. 305–330, 1976.

[14] J. C. Stevens and L. E. Marks, "Spatial summation and the dynamics of warmth sensation," *Perception & Psychophysics*, vol. 9, no. 5, pp. 391–398, 1971.

[15] J. Stevens and L. Marks, "Spatial summation of cold," *Physiology & Behavior*, vol. 22, no. 3, pp. 541–547, 1979.

[16] R. Defrin, A. Benstein-Sheraizin, A. Bezalel, O. Mantzur, and L. Arendt-Nielsen, "The spatial characteristics of the painful thermal grill illusion," *Pain*, vol. 138, no. 3, pp. 577–586, 2008.

[17] S. Alrutz, "On the temperature-senses," *Mind*, vol. 6, no. 3, pp. 445–448, 1897.

[18] T. Thunberg, "Förnimmelserne vid till samma ställe lokaliserad, samtidigt pägäende köld-och värmeretning," *Uppsala Läkfören Förh*, vol. 1, pp. 489–495, 1896.

[19] A. Craig and M. Bushnell, "The thermal grill illusion: unmasking the burn of cold pain," *Science*, vol. 265, no. 5169, pp. 252–255, 1994.

[20] H. Goldsmid, *Thermoelectric refrigeration*. Springer, 2013.

[21] A. Standard, "Standard 55-2004. thermal environment conditions for human occupancy. ashrae," *Atlanta, USA*, 2010.

[22] J. D. Greenspan and D. R. Kenshalo, "The primate as a model for the human temperature-sensing system: 2. area of skin receiving thermal stimulation (spatial summation)," *Somatosensory & Motor Research*, vol. 2, no. 4, pp. 315–324, 1985.

[23] S. L. Berg, "Magnitude estimates of spatial summation for conducted cool stimuli along with thermal fractionation and a case of secondary hyperalgesia." Ph.D. dissertation, ProQuest Information & Learning, 1979.

[24] H. Hensel and T. Huopaniemi, "Static and dynamic properties of warm fibres in the infraorbital nerve," *Pflügers Archiv*, vol. 309, no. 1, pp. 1–10, 1969.

[25] H. Hensel and R. Wurster, "Static behaviour of cold receptors in the trigeminal area," *Pflügers Archiv*, vol. 313, no. 2, pp. 153–154, 1969.

[26] R. Melzack, G. Rose, and D. McGinty, "Skin sensitivity to thermal stimuli," *Experimental neurology*, vol. 6, no. 4, pp. 300–314, 1962.

[27] I. Kojo and A. Pertovaara, "The effects of stimulus area and adaptation temperature on warm and heat pain thresholds in man," *International journal of neuroscience*, vol. 32, no. 3-4, pp. 875–880, 1987.

[28] L. M. Harding and A. R. Loescher, "Adaptation to warming but not cooling at slow rates of stimulus change in thermal threshold measurements," *Somatosensory & motor research*, vol. 22, no. 1-2, pp. 45–48, 2005.