Cold or Hot? How Thermal Stimuli Are Related to Human Emotional System?

Katri Salminen[1], Veikko Surakka[1], Jukka Raisamo[2], Jani Lylykangas[1], Roope Raisamo[2], Kalle Mäkelä[3], and Teemu Ahmaniemi[4]

[1,2] Tampere Unit for Computer-Human Interaction, Kanslerinrinne 1, 33014, University of Tampere, Finland
[1] Research Group for Emotions, Sociality, and Computing
[2] Multimodal Interaction Research Group
{katri.salminen,veikko.surakka,jukka.raisamo, jani.lylykangas,roope.raisamo}@sis.uta.fi
[3] Tampere University of Technology, Department of Electronics, P.O. Box 692, 33101 Tampere
kalle.makela@tut.fi
[4] Nokia Research Center, Itämerenkatu 11 – 133, 00180 Helsinki, Finland
teemu.ahmaniemi@nokia.com

Abstract. The aim was to study emotional responses to thermal stimulation. Stimuli were varied by increasing or decreasing temperature by 2, 4 or 6°C in respect to the participants' hand temperature. The stimuli were either dynamic (i.e. heated or cooled while touching) or pre-adjusted (i.e. heated or cooled to the target temperature before touching). The results showed, for example, that 6°C change in temperature was rated as unpleasant, arousing, dominant, and avoidable especially when the stimulus was warm. 4°C increase was rated as arousing, dominant, and pleasant. In addition, pre-adjusted 6°C increase elevated the physiological arousal in terms of skin conductance response.

Keywords: Affective haptics, Thermal stimulation, Human emotions.

1 Introduction

We often use thermal attributes while describing meaningful events in our lives. For example, over a lunch hour conversation we can describe someone as a warm person or as cold as ice. Meeting an old friend by coincidence can be heartwarming while losing a dear pet can make one feel cold inside. Therefore, it is not surprising that temperature is frequently argued to be connected with sociality and emotions. Already in the 1950's Harlow [1] showed that touch and warmth of a caregiver was essential for normal social and emotional development of monkey infants. Temperature has also short term effects on social behavior. For example, holding a cup containing warm coffee was found to make one characterize other people in more positive manner than holding a cup containing cold coffee [2]. In general, it seems that the experience of pleasantness is affected by thermal stimulation so that warm temperatures are perceived as comfortable and pleasant [3] while cold temperatures are perceived as uncomfortable [4].

I. Oakley and S. Brewster (Eds.): HAID 2013, LNCS 7989, pp. 20–29, 2013.

In human-technology interaction (HTI) thermal stimulation has been studied in a lesser extent. Most of the previous studies have concentrated, for example, on providing information on the temperature of objects via thermal sense [5]. The results have shown that people are able to recognize object surface materials (e.g. foam or copper) based on only thermal information. In these studies participants' hands have been preheated to improve thermal sensitivity.

A recent study [6] has mapped how easily people can recognize small changes in temperature when the stimulation is provided, for instance, to arm area with thermal actuators. In this study also the subjective experience of thermal comfort was taken into account by asking the participants whether the stimulus was uncomfortable or comfortable. The results showed that people can detect even one degree temperature changes, and that intense temperature changes (e.g. 6°C) are experienced as more uncomfortable than less intense changes (e.g. 1°C).

Systematic studies mapping emotional responses to thermal stimuli are virtually non-existent in the field of HTI. When studying ratings of emotional responses to haptic stimulation [7], the use of bipolar rating scales has been functional. These rating scales are based on the dimensional theory of emotions which suggests that there are three basic dimensions (pleasantness, arousal, and dominance) covering the dimensional emotional space when rating different types of stimuli [8]. As these three dimensions have been associated to a fourth dimension (i.e. ones' approach – withdrawal behavior) this motivational tendency has recently been measured as well [9]. In addition, in emotion studies psychophysiological responses to stimuli are often detected. Especially, the level of emotional arousal can be analyzed using the skin conductance response (SCR) measurement. SCR is argued to be faster and higher in magnitude to arousing stimuli and slower and smaller in magnitude to calming stimuli [10].

Studying thermal stimulation can be challenging. The temperature of the skin is dependent on the current body temperature, and it fluctuates based on environmental conditions. In addition, when the user operates with a device equipped with thermal actuator, the temperature of the thermal actuator is roughly the same as the user's hand. Thus, the skin temperatures should be defined (i.e. measured) before stimulus presentation in order to be able to stimulate the participants hand exactly with certain temperatures. Therefore, we have chosen an approach where we first measure the participants hand temperature and then present the change in temperature (i.e., stimulus) in respect to that temperature.

In a pilot study [11] we tested how thermal stimulation might evoke emotions. Two target temperatures (4°C increase and decrease in respect to the hand temperature) were presented to the participants with two presentation methods (i.e. pre-adjusted and dynamic). The task was to rate the stimuli with previously mentioned emotion-related scales while SCR was measured. A 4°C increase was rated as arousing and dominant when compared to 4°C decrease suggesting that warm stimuli are activating the dimensions of arousal and dominance while cold stimuli do that in a lesser degree. The SCR was higher in magnitude when the stimulus was warm than when the stimulus was cold confirming the results of subjective ratings of arousal. Interestingly, the presentation method affected the speed of the SCR. The warm stimuli activated the SCR faster when the stimulus was pre-adjusted and cold when the stimulus was dynamic. Together, both obtained SCR results suggest that SCR is responding mostly to pre-adjusted stimuli. However, it the temperature is cold, dynamic presentation method may be better to evoke a rise in SCR.

Even though the results of the pilot study indicated that thermal stimuli can be related to the functioning of human emotional system, the study had several limitations. First, we had only 8 participants. Second, only two target temperatures were used. Third, the algorithm used to create the stimuli was sensitive to the contact with the skin so that, for example, when the participant was touching the thermal actuator when it was cold the temperature was slightly shifted towards to the hand temperature from the aimed target temperature. Therefore, the results were only indicative of the way temperature variations could affect human emotions. In the current study we aimed to gain further insight about temperature and emotions. For this purpose, we recruited 24 participants and presented them six target temperatures with two presentation methods. The algorithm for stimulus presentation was improved. Participants rated the stimuli with four emotion-related rating scales and one asking their ratings about the temperature. Physiological responses were analyzed by SCR measurements.

2 Methods

2.1 Participants

24 voluntary participants (12 female and 12 male with a mean age of 25.4 years, range 18–46) took part in the study. All had normal sense of touch by their own report. Their mean hand temperature was 30.3°C (range 23.9–33.5°C). The experiment was approved by the Department of Science Center of the Pirkanmaa hospital district.

2.2 Apparatus

The thermal stimuli were provided with a Peltier thermal actuator. The actuator contained a Multicomp PF-031-10-25 (15mm x 15mm x 4.8mm) thermoelectric module attached to an aluminum heatsink with double-sided heat-conducting tape. The actuator also had an integrated Labfacility DM-310 PT1000 temperature sensor attached to the surface of the actuator to monitor the temperature of the actuator. The actuator was driven with a driver module that was hosted by an Atmel ATmega324P microcontroller to receive drive instructions via serial connection and convert the instructions into PWM signal to drive the actuator accordingly. E-Prime 2.0 Professional® application suite [12] was used for running the experiment and for collecting the user input. An Arduino prototyping platform with Atmel ATMega328P was used both for controlling the driver module via serial connection and for listening to another serial connection where E-Prime sent the ID of the next stimulus. After receiving the stimulus ID Arduino queried the temperature of the hand placed over a Melexis MLX90614 IR temperature sensor. Then, Arduino used a simple proportional–integral-derivative (PID) control loop to adapt the Peltier temperature close to that of the hand to meet the starting condition. Third, Arduino used the PID control loop to meet the parameters defined by the current stimulus with the user's hand placed over the Peltier actuator. When running the control loop the driver module constantly sent temperature data from the actuator that was used to refine the driving instructions. All the temperature data received from the actuator as well as the initial hand and room temperature measurements were written to a log for later inspection. The control loop was programmed to monitor the surface temperature of the Peltier during the stimulus presentation. If the temperature of the Peltier actuator went below 17°C or above 43°C, the experiment was automatically terminated. This was done avoid the possibility of the actuator to damage the skin (e.g., cause skin burn). The SCR was measured with Nexus-10 platform and Biotrace+ software version 2010A. A Bluetooth connection was used to transfer SCR data to a laptop PC during the measurement.

2.3 Design and Stimuli

The experiment was a within-subject repeated measures design. Six target temperatures were created by decreasing or increasing the stimulus temperature by 2, 4 or 6°C in respect to the participants hand temperature measured before the stimulus presentation. The stimuli were divided in two groups based on whether the presentation method was dynamic or pre-adjusted. When the presentation method was dynamic, the participants sensed the cooling or heating towards the target temperature during the stimulus presentation. When the presentation method was pre-adjusted the stimulus was heated to the target temperature before the participant was allowed to touch the stimulus, and then the temperature was kept constant during stimulus presentation. To compare the possible effects of thermal variation to a neutral reference point, a stimulus where the temperature was kept constant at the participant's hand temperature (i.e. neutral stimulus) was presented in both stimulus groups. Therefore, we had a total of 14 stimuli (i.e. dynamic increase or decrease of 2, 4 and 6°C, pre-adjusted increase or decrease of 2, 4 and 6°C, and two neutral stimuli). Because the hand temperature of the participants varied, the participant with lowest hand temperature received stimuli at the range of 17.9 - 29.9°C, and the participant with highest hand temperature at the range of 27.5 - 39.5°C.

2.4 Procedure

After arriving to the laboratory the participant was seated in a chair, sensors to measure SCR throughout the experiment were attached to the participants' nondominant hand's index finger and middle finger. The experiment was divided in two experimental blocks. In the first block a stimulus presentation trial proceeded as follows. The participant put the dominant hand's palm on the infrared sensor for 10 s to measure the current hand temperature with a sampling rate of 10 Hz. The average of these measurements was used as the current hand temperature. Then, the participant put the same palm on the Peltier actuator to feel a thermal stimulus. The presentation time depended on the stimulus so that when the presentation method was pre-adjusted the stimulus was always presented for 10 s. However, when the presentation method was dynamic, the temperature change was roughly 0.5°C/s so that the presentation time was either 4 s (2°C change), 8 s (4°C change) or 12 s (6°C change). The neutral stimulus was presented in both stimulus groups for 10 s. After the stimulus presentation the participant was instructed to rate the stimulus with four nine-point scales for pleasantness (varying from "the stimulus felt unpleasant" to "the stimulus felt pleasant"), approachability (varying from "the stimulus felt avoidable" to "the stimulus felt approachable"), arousal (varying from "I felt calm during stimulus presentation" to "I felt aroused during stimulus presentation"), and dominance (varying from "I was in control during stimulus presentation" to "the stimulus was in control during presentation"). The mid-point of each scale represented a neutral experience (i.e., the stimulus felt neither unpleasant nor pleasant). The participant was instructed to rate the immediate impression of the stimulus. The next trial was initialized after the participant had rated one stimulus with all the four scales. The second block proceeded similarly to the first block except that instead of emotional ratings the participants rated their experience of the stimulus temperature with a nine-point scale varying from cold to hot. The mid-point of the scale represented a neutral experience (i.e. the stimulus felt neither cold nor hot). The order of both the stimulus groups and rating scales was fully counterbalanced. In addition, the stimulus presentation was fully randomized within a group. The total amount of stimulus presentation trials was 28. Conducting the experiment took approximately 45 minutes.

2.5 Data Analysis

The subjective rating data was first analyzed with Friedman tests in order to test whether varying the temperature of dynamic stimuli affected the ratings. Then, Friedman test was used to test whether varying the temperature of pre-adjusted stimuli affected the ratings. If statistically significant differences were found, Wilcoxon signed-ranks test were used for pairwise comparisons. Wilcoxon signed-ranks test was also used to test whether the presentation method affected the ratings (e.g. dynamic and pre-adjusted 6°C increases were compared). The rise time (i.e. the time from the beginning of the response until the highest peak) and the magnitude (i.e. the highest peak) of the SCR were analyzed with the within-subject repeated measures analysis of variance (ANOVA). The SCR reactions were calculated from the data collected in the first experimental block during 5000 ms time frame from the stimulus onset (i.e. 1000 to 6000 ms). Three participants were excluded from the SCR analysis due to technical problems. Bonferroni corrected pairwise comparisons were used as post hoc tests.

3 Results

Friedman tests showed that the temperature affected the ratings of pleasantness when the stimuli were dynamic $\chi = 28.1$, $p < 0.001$. However, when the pre-adjusted stimuli were compared no statistically significant differences were found $\chi = 11.5$, $p > 0.05$. Tables 1-3 show the results of the Wilcoxon signed-ranks tests when the presentation method was dynamic. Because the pre-adjusted method showed no statistically significant findings, the results are not included in the table for the ratings of pleasantness. Wilcoxon signed-ranks test showed also that the presentation method affected the pleasantness ratings. When the temperature was -6°C, pre-adjusted stimulus was rated as more pleasant than dynamic stimulus $T = 2.8$, $p < 0.01$. The pre-adjusted stimulus was also rated as more pleasant than dynamic stimulus when the temperature change was +4°C, $T = 2.3$, $p < 0.05$, and +6°C $T = 2.4$, $p < 0.05$.

Friedman tests showed that the temperature affected the ratings of approachability when the presentation method was dynamic $\chi = 32.4$, $p < 0.001$ and when it was pre-adjusted $\chi = 17.6$, $p < 0.01$. Tables 1-3 show the results of the Wilcoxon signed-ranks tests. Wilcoxon signed-ranks test showed also that the presentation method affected the approachability ratings but only when the temperature was increased. Pre-adjusted stimuli were rated as more approachable than dynamic stimuli when the temperature change was +2°C $T = 2.5$, $p < 0.05$, +4°C $T = 2.4$, $p < 0.05$, and +6°C $T = 2.4$, $p < 0.05$.

Friedman tests showed that the temperature affected the ratings of arousal when the presentation method was dynamic $\chi = 64.7$, $p < 0.001$ and when it was pre-adjusted $\chi = 50.5$, $p < 0.001$. Tables 1-3 show the results of the Wilcoxon signed-ranks tests. Wilcoxon signed-ranks test did not show any statistical significant differences between temperatures for the ratings of arousal when the presentation method was varied.

Friedman tests showed that the temperature affected the ratings of dominance when the presentation method was dynamic $\chi = 78.9$, p < 0.001 and when it was pre-adjusted $\chi = 70.9$, p < 0.001. Tables 1-3 show the results of the Wilcoxon signed-ranks tests. Wilcoxon signed-ranks test showed also that the presentation method affected the dominance ratings. Dynamic stimuli were rated as more dominant than pre-adjusted stimuli when the temperature change was -6°C $T = 2.1$, $p < 0.05$, -2°C $T = 2.1$, $p < 0.05$, and +6°C $T = 2.3$, $p < 0.05$.

Friedman tests showed that the temperature affected the ratings of temperature when the presentation method was dynamic $\chi = 119.6$, $p < 0.001$ and it was pre-adjusted $\chi = 127.1$, $p < 0.001$. Tables 1-3 show the results of the Wilcoxon signed-ranks tests. Wilcoxon signed-ranks test showed also that the presentation method affected the temperature ratings. Pre-adjusted stimuli were rated as hotter than dynamic stimuli when the temperature change was -6°C $T = 2.1$, $p < 0.05$, or -4°C $T = 2.5$, $p < 0.05$. However, when the temperature change was +6°C, dynamic stimulus was rated as hotter than pre-adjusted stimulus $T = 3.8$, $p < 0.001$.

Tables 1-3. Pairwise comparisons between the subjective ratings. The temperatures being compared are on the top of the table, and the rating scale on the left of the table. Each cell is divided in two parts. On the white area of the cell there are pairwise comparisons for the stimuli with dynamic presentation method and on the blue area for the stimuli with pre-adjusted presentation method. In each cell there is Wilcoxon's T value, the temperature change rated as, for example, more pleasant or hotter and indication of P value ($p < 0.05$*, $p < 0.01$**, and $p < 0.001$***) for both presentation methods. Ns stands for non-significant.

Table 1.

	-6 vs -4	-6 vs -2	-6 vs 0	-6 vs +2	-6 vs +4	-6 vs +6	-4 vs -2
pleasantness dyn	T = 2.0 [-4] *	ns	ns	ns	ns	T = 2.2 [-6] *	ns
approachal dyn	T = 2.5 [-4] *	ns	ns	ns	ns	T = 2.3 [-6] *	ns
approachal pre	ns	ns	ns	ns	ns	ns	ns
arousal dyn	T = 2.4 [-6] *	T = 2.3 [-6] *	T = 2.6 [-6] **	ns	ns	T = 3.4 [+6] ***	ns
arousal pre	ns	ns	ns	ns	T = 2.5 [+4] *	T = 2.9 [+6] **	ns
dominance dyn	T = 3.2 [-6] **	T = 3.3 [-6] ***	T = 3.5 [-6] ***	T = 2.1 [-6] *	ns	T = 2.9 [+6] **	ns
dominance pre	T = 2.5 [-6] *	T = 3.3 [-6] ***	ns	ns	T = 2.7 [+4] **	T = 3.5 [+6] **	ns
temperature dyn	ns	T = 3.7 [-2] ***	T = 4.0 [0] ***	T = 4.2 [+2] ***	T = 4.2 [+4] ***	T = 4.3 [+6] **	T = 4.1 [-2] ***
temperature pre	T = 2.3 [-4] *	T = 3.5 [-2] ***	T = 3.9 [0] ***	T = 4.3 [+2] ***	T = 4.2 [+4] ***	T = 4.3 [+6] **	T = 3.6 [-2] ***

Table 2.

	-4 vs 0	-4 vs +2	-4 vs +4	-4 vs +6	-2 vs 0	-2 vs +2	-2 vs +4
pleasantness dyn	ns	ns	ns	T = 3.1 [-4] **	ns	ns	ns
approachal dyn	ns	ns	ns	T = 3.2 [-4] ***	ns	ns	ns
approachal pre	ns	ns	ns	T = 2.6 [-4] **	ns	ns	ns
arousal dyn	ns	ns	T = 2.8 [+4] **	T = 4.1 [+6] ***	ns	T = 2.3 [+2] *	T = 3.3 [+4] ***
arousal pre	ns	ns	T = 3.4 [+4] **	T = 3.6 [+6] ***	ns	ns	T = 3.9 [+4] ***
dominance dyn	ns	ns	T = 3.1 [+4] **	T = 4.1 [+6] ***	ns	ns	T = 3.5 [+4] **
dominance pre	ns	ns	T = 3.8 [+4] ***	T = 4.1 [+6] ***	ns	T = 2.4 [+2] *	T = 3.9 [+4] ***
temperature dyn	T = 4.2 [0] ***	T = 4.3 [+2] ***	T = 3.7 [+4] ***	T = 4.3 [+6] ***	ns	T = 3.9 [+2] ***	T = 3.6 [+4] ***
temperature pre	T = 3.7 [0] ***	T = 4.3 [+2] ***	T = 4.3 [+4] ***	T = 4.3 [+6] ***	T = 2.8 [0] *	T = 4.1 [+2] ***	T = 4.4 [+4] ***

Table 3.

	-2 vs +6	0 vs +2	0 vs +4	0 vs +6	+2 vs +4	+2 vs +6	+4 vs +6
pleasantness dyn	T = 2.9 [-2] **	ns	T = 2.0 [0] *	T = 3.9 [0] ***	T = 2.0 [+2] *	T = 3.6 [+2] ***	T = 3.5 [+4] ***
approachal dyn	T = 2.7 [-2] **	ns	T = 2.5 [0] *	T = 4.0 [0] ***	ns	T = 3.2 [+2] ***	T = 3.5 [+4] ***
approachal pre	T = 2.3 [-2] *	ns	ns	T = 3.3 [0] ***	ns	T = 3.1 [+2] **	T = 3.0 [+4] **
arousal dyn	T = 3.7 [+6] ***	T = 2.0 [+2] *	T = 3.5 [+4] ***	T = 4.0 [+6] ***	T = 2.7 [+4] **	T = 3.9 [+6] ***	T = 3.9 [+6] ***
arousal pre	T = 3.7 [+6] ***	ns	T = 3.7 [+4] ***	T = 3.9 [+6] ***	T = 2.6 [+4] **	T = 3.1 [+6] **	ns
dominance dyn	T = 4.1 [+6] ***	T = 2.0 [+2] *	T = 4.0 [+4] ***	T = 4.3 [+6] ***	T = 3.4 [+4] ***	T = 4.3 [+6] ***	T = 3.6 [+6] ***
dominance pre	T = 4.0 [+6] ***	ns	T = 3.7 [+4] ***	T = 4.0 [+6] ***	T = 3.0 [+4] **	T = 3.7 [+6] ***	ns
temperature dyn	T = 4.3 [+6] ***	T = 3.6 [+2] ***	T = 3.6 [+4] ***	T = 4.4 [+6] ***	T = 2.9 [+4] **	T = 4.3 [+6] ***	T = 4.2 [+6] ***
temperature pre	T = 4.3 [+6] ***	T = 3.5 [+2] ***	T = 4.2 [+4] ***	T = 4.3 [+6] ***	T = 3.4 [+4] **	T = 4.4 [+6] ***	T = 3.6 [+6] ***

For the rise time of the SCR a 2 × 7 (presentation method × temperature change) ANOVA showed no statistically significant effects of the stimuli. For the magnitude of the SCR a 2 × 7 (presentation method × target temperature) ANOVA showed a statistically significant interaction of the main effects of presentation method and target temperature $F(1,6) = 6.21$, $p < 0.001$. To analyze the interaction of the main effects, two one-way ANOVA's were performed to test whether the used target temperatures elevated the SCR differently when the presentation method was dynamic than when it was pre-adjusted. One-way ANOVA's showed that when the presentation method was dynamic, there were no statistically significant differences in the magnitude of the SCR between different target temperatures $F(1,6) = 2.2$, $p > 0.05$. However, when the presentation method was pre-adjusted there were statistically significant differences in the magnitude of the SCR between different target temperatures $F(1,6) = 10.3$, $p < 0.001$. Bonferroni corrected pairwise comparisons showed that the statistically significant result was due to the fact that pre-adjusted 6°C increase in temperature elevated the magnitude of SCR more than 6°C decrease $MD = 0.29$, $p < 0.01$, 4°C decrease $MD = 0.29$, $p < 0.01$, 2°C decrease $MD = 0.35$, $p < 0.01$, 0°C $MD = 0.23$, $p < 0.01$, or 2°C increase $MD = 0.22$, $p < 0.01$.

4 Discussion

The participants rated 6°C increase as less pleasant than any other stimuli but only when the presentation method was dynamic. A 6°C increase in both dynamic and pre-adjusted method was rated as less approachable than any of the other stimuli. Warm stimuli were in general rated as arousing and dominant so that the higher the intensity, the more arousing and the more dominant rating (e.g. 6°C increase was rated as more arousing and dominant than 2°C increase or decrease). High intensity cold stimulus (i.e. 6°C decrease) was rated as more arousing and dominant than the other cold stimuli when the presentation method was dynamic. It should be noted that even the high intensity cold stimuli were always rated as less arousing and less dominant than any of the warm stimuli. In addition, the dynamic stimuli were rated as less pleasant and approachable but more dominant than pre-adjusted stimuli especially when stimulus temperature was warm.

The participants also rated the stimuli adequately in respect to the experienced temperature despite of the presentation method. This result suggesting that 2°C changes are sufficient for creating distinguishable thermal stimuli for haptic user interfaces is in line with earlier findings [6, 11]. However, also the presentation method affected the ratings so that, for example, 6°C increase was rated as hotter when the presentation method was dynamic than when it was pre-adjusted. This result may be due to the reason that when the method is pre-adjusted, the participant is able to feel the stimulus temperature immediately after touching the actuator. But when the stimulus presentation is dynamic the participant may become cautious about the final limit of heating.

SCR measurements showed that only pre-adjusted 6°C increase significantly elevated the SCR. It seems possible that when the temperature changes during touching the actuator the autonomic nervous system (ANS) adapts to the change in the temperature but when the shift in stimulus temperature is abrupt (i.e., presentation method is pre-adjusted) there is no time to adapt and therefore a stronger ANS response is triggered.

In general, the use of wider set of temperature changes than in a pilot study [11] clearly gave new fine grained insight. Unlike in the pilot study, now the ratings of pleasantness and approachability were affected by temperature changes. 6°C increase was rated as unpleasant and avoidable while 2°C increase was rated as rather pleasant and approachable. 4°C shift in temperature in respect to the hand temperature was rated as rather neutral. So, it seems that in respect to experiences of pleasantness and approachability, smaller (e.g. 2°C) or larger (e.g. 6°C) shifts in temperature (in contrast to the 4°C shifts used earlier) are more effective.

In a previous study [6] there was a tendency to rate cold stimuli as more comfortable than warm stimuli. Also the stimulus intensity affected the experience of thermal comfort so that the warm stimuli with higher intensity were in general rated as less comfortable than the stimuli with lower intensity. Our current results seem to contradict this finding at some degree. As in the previous study warm stimuli with high intensity were rated as rather unpleasant. However, this result was evident only with dynamic presentation method. Therefore, it seems that the experience of comfort or pleasantness is not tied to the stimulus intensity or temperature alone, but the way the temperature is presented to the user. This may indicate that instead of temperature as such, the change in temperature is the factor making the experience of thermal stimulation as pleasant or unpleasant.

The dimensional theory of emotions [8] suggests that the elevated level of arousal represents the activation of the motivational tendency related to approaching or avoiding the stimulation. The pre-adjusted warm stimuli were rated as arousing yet pleasant. Then, dynamic stimuli were in general rated as more dominant but less pleasant and approachable than pre-adjusted stimuli. This suggests that the pre-adjusted stimuli can be used to make the stimuli arousing and approachable while dynamic presentation method makes the stimuli avoidable.

In a practical scenario a thermal actuator would be attached to the back of a mobile phone to provide stimuli to the user's palm. A pre-adjusted stimulus is provided if the mobile phone is, for instance, on the table and the user touches the phone after stimulus has reached the target temperature. A dynamic stimulus is provided, for example, when the user is holding the mobile phone during a phone call. Intuitively, stimulus rated as arousing and dominant could be used to efficiently catch the users' attention. In addition, the stimulus should be pleasant. A 4°C increase is suitable for this purpose with both presentation methods.

The current results could be tested with interfaces utilizing auditory feedback. At this point, the results can only be speculated. There is some evidence that vibrotactile feedback in conjunction with speech works mostly as emphasizing emotional content of the speech (e.g. making it more arousing) [13]. Based on the current results seems likely that thermal stimulation could be used to communicate information related both to pleasantness and arousal in conjunction with speech. This assumption could be supported by the fact that thermal stimulation is processed differently than vibrotactile stimulation in skin and at the central nervous system level.

In summary, the results suggest that warm stimuli work better than cold and neutral stimuli in activating human emotional system when measured with both subjective rating scales and physiological responses. If one wants to elevate the level of arousal and dominance, at least 4°C increase in temperature is needed. A pre-adjusted presentation method is more suitable for this purpose than dynamic presentation method as in general pre-adjusted stimuli were rated as more pleasant and approachable. The stimuli with pre-adjusted presentation method also affected the physiological responses more efficiently than the stimuli with dynamic presentation method suggesting that ANS is affected more when the stimulus is pre-adjusted than when it is dynamic. These results can be seen as a step forward in the knowledge needed in creating devices that are capable of using thermal feedback as a haptic interaction method.

Acknowledgments. This research was a part of HEI project funded by the Finnish Funding Agency for Technology and Innovation (Tekes). In addition, the research was supported by Tampere Doctoral Programme in Information Science and Engineering (TISE), and the HapticAuto project (Tekes decision number 40289/11).

References

1. Harlow, H.F.: The nature of love. American Psychologist 13(2), 673–685 (1958)
2. Williams, L.E., Bargh, J.A.: Experiencing physical warmth promotes interpersonal warmth. Science 322, 606–607 (2008)
3. Kanosue, K., Sadato, N., Okada, T., Yoada, T., Nakai, S., Yoshida, K., Hosono, T., Nagashima, K., Yagishita, T., Inoue, O., Kobyashi, K., Yonekua, Y.: Brain activation during whole body cooling in humans studied with functional magnetic resonance imaging. Neuroscience Letters 329, 157–160 (2002)
4. Sung, E.-J., Yoo, S.-S., Yoon, H.W., Han, S., Park, H.W.: Brain activation related to affective dimension during thermal stimulation in humans: A functional magnetic resonance imaging study. International Journal of Neuroscience 117, 1011–1027 (2007)
5. Jones, L.A., Ho, H.: Warm or cool, large or small? The challenge of thermal displays. IEEE Transactions on Haptics 1, 53–70 (2008)
6. Wilson, G., Halvey, M., Brewster, S.A., Hughes, S.A.: Some like it hot: thermal feedback for mobile devices. In: CHI 2011, pp. 2555–2564 (2011)
7. Salminen, K., Surakka, V., Lylykangas, J., Raisamo, J., Saarinen, R., Rantala, J., Raisamo, R., Evreinov, G.: Emotional and behavioral responses to haptic stimulation. In: CHI 2008, pp. 1555–1562 (2008)
8. Bradley, M.M., Lang, P.J.: Measuring emotion: the self-assessment manikin and the semantic differential. Journal of Behavior Therapy and Experimental Psychiatry 25, 49–59 (1994)
9. Davidson, R.J.: Cerebral asymmetry, emotion and affective style. In: Davidson, R.J., Hugdahl, K. (eds.) Brain Asymmetry, pp. 361–387. The MIT Press, Cambridge (1995)
10. Witvliet, C.V.O., Vrana, S.R.: Psychophysiological responses as indices of affective dimensions. Psychophysiology 32, 436–443 (1995)
11. Salminen, K., Surakka, V., Raisamo, J., Lylykangas, J., Pystynen, J., Raisamo, R., Mäkelä, K., Ahmaniemi, T.: Emotional responses to thermal stimuli. In: ICMI 2011, pp. 193–196 (2011)
12. Schneider, W., Eschman, A., Zuccolotto, A.: E-Prime User's Guide. Psychology Software Tools, Inc., Pittsburgh (2002)
13. Salminen, K., Surakka, V., Lylykangas, J., Rantala, J., Ahmaniemi, T., Raisamo, R., Trendafilov, D., Kildal, J.: Tactile Modulation of Emotional Speech Samples. In: Adv. Human-Computer Interaction 2012 (2012)