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# Perception of Thermal Stimuli for Continuous Interaction

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**Abstract**

Thermal stimulation represents a relatively unexplored and potentially beneficial area of research for interface design. To date no research on thermal interfaces has looked at continuous thermal stimulation in detail. Here we begin to explore the design space offered by continuous thermal stimulation by conducting a controlled experiment that investigates perception of various thermal stimuli relative to a range of starting temperatures. Based on the experimental results, we discuss design implications and possible future work.

**Author Keywords**

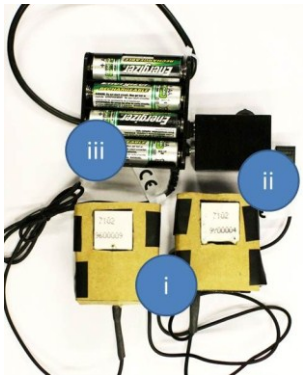
Thermal; non-visual; feedback; widgets;

**ACM Classification Keywords**

H.5.2. User Interfaces: Haptic IO

**Introduction**

Thermal stimulation is a rich, emotive and salient output modality that has a lot of potential for use in HCI, but which has only begun to be fully explored. There are a range of potential benefits to thermal feedback: it is private as it produces no audio or visual cues, it can act as an alternative non-visual feedback channel when audio or vibrotactile are not appropriate, and it has an affective aspect [4, 6]. Example uses include eyes free navigation [7], augmentation of



**Figure 1:** Apparatus including Peltier stimulators



**Figure 2:** Area stimulated

media [4] and ambient interaction [3, 7]. Many of these potential uses for thermal stimulation employ continuous/dynamic interaction, e.g. the device is constantly warming or cooling on a scale to assist navigation through eyes-free ambient notifications. However, the majority of HCI research on thermal stimulation has focused on single prototype applications or has looked at stimulation from one fixed point to a small number of other fixed points [1, 2, 8, 9]. To date, only Wettach *et al.* [7] have tried to provide design recommendations for continuous thermal feedback, which was limited to a small range of warm changes and did not try to exploit the full range of human thermal sensitivity. The work in this paper begins to explore a wider range of temperatures that can be used in feedback. To achieve this we conducted a controlled experiment that investigated perception of various thermal stimuli relative to a range of starting temperatures. The main aim of the experiment was to test detection and subjective comfort and intensity ratings of various starting points and temperature changes for thermal feedback, which lets us know, for example, how many degrees of freedom can be used for expressing information thermally. It is hoped this work will eventually lead to the implementation of thermal widgets, like the work of Ramos *et al.* [5] on pressure widgets. Example widgets include a thermal progress bar, which would warm or cool to indicate progress, or a thermal contact list which could display availability in an eyes-free manner via temperature.

### Thermal Space Experiment

#### Apparatus

A microcontroller (Figure 1(ii)) connected to a two-channel Peltier heat pump (Figure 1(i)) designed and built by SAMH Engineering was used. Both Peltiers

could be independently controlled via Bluetooth, with the temperature set anywhere between  $-20^{\circ}\text{C}$  and  $+45^{\circ}\text{C}$ , accurate to  $\sim 0.1^{\circ}\text{C}$ . The apparatus was powered by 4 AA batteries (Figure 1(iii)); these could power the Peltiers to stay at a constant temperature for up to 8 hours. This apparatus has been used in previous evaluations [8] and it is small enough to be easily added to other equipment in future research.

#### Stimuli

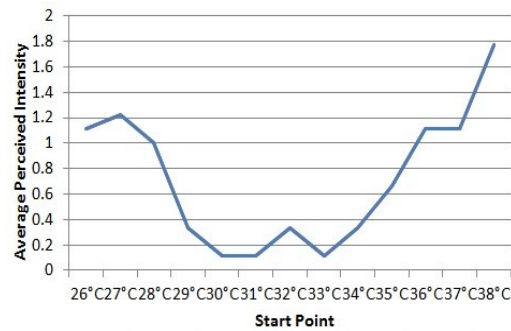
As continuous stimulation involves thermal changes across a range of temperatures, we used 13 different temperatures as starting points from which to test detection of stimuli. The temperatures were every whole  $1^{\circ}\text{C}$  in the range of  $26\text{--}38^{\circ}\text{C}$ . This range has been used in a number of previous evaluations and forms the basis for existing design recommendations [1, 2, 9]. It also covers the skin's natural resting temperature [6]. The skin was adapted (i.e. matched) to each starting point before each trial session by warming/cooling it and was returned to the starting point between each stimulus presentation. Whether adaptation occurs depends on whether the temperature sits within the individual's homeostatic neutral zone [6]. While each individual may have different skin temperatures, by deliberately adapting the skin within the neutral zone, something it would do naturally anyway, we recreated these natural situations allowing for more data to be gathered more easily. This also allows us to measure perception from a wide range of potential starting skin temperatures, meaning that our findings are applicable for real situations. A "round-robin" style of experiment was designed, so that the Peltiers would change from every temperature (in divisions of  $1^{\circ}\text{C}$ ) to every other temperature in the range. As a result of visiting each point in the range, in

most cases both warming and cooling stimuli were presented e.g. starting from 32°C, a change to 28°C is a cooling change and a change to 36°C is a warming change. The exceptions were 26°C and 38°C, as they are the extremes of the scale. Two different rates of stimulus change (ROC) were used: 1°C/sec and 3°C/sec. ROC has been shown to influence perception of thermal stimuli [1, 2, 9] and this allowed us to compare our results with other findings. In addition ROC increases intensity, so we can see how the salience of changes within the range is influenced by ROC. Using a slower ROC may be appropriate for ambient feedback, while faster rates might be more attention grabbing. Thus, from each starting point, 24 stimuli (12 intensity end points x 2 ROC) were presented. All stimuli were presented to the thenar eminence (Figure 2), as it has increased sensitivity in comparison to other body parts [9] and it was easy for participants to place and remove their thenar from the stimulator if it becomes uncomfortable. The thenar was also chosen as it represents the most likely location for thermal presentation if using a mobile device or computer mouse etc. and it has been used in a number of other evaluations, making it good for comparison [1, 2, 9].

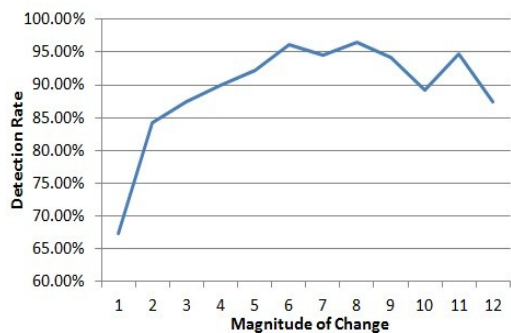
#### *Procedure and Design*

Each participant was seated indoors at a desk upon which there was a laptop and mouse. The Peltier stimulators (see Figure 1(i)) lay on the desk in front of the participant, facing up so that he/she could lay their non-dominant hand on the stimulator. At the start of each condition within the experiment the Peltiers were set to a randomly selected starting temperature in the range of 26-38°C for one minute. After this, we recorded subjective reports of the intensity of the start

point (4-point Likert scale from "Neutral" to "Very Hot/Cold") and the comfort level of the start point (7-point Likert scale from "Very Comfortable" to "Very Uncomfortable"). The thermal stimuli were then presented in a reverse staircase fashion, working from perception to non-perception. That is, from each starting point,  $S$ , a direction (warming or cooling) and ROC were randomly chosen and a stimulus with the greatest possible magnitude of temperature change ( $\Delta t$ ) from that starting point and direction was presented e.g.  $S = 38^\circ\text{C}$ ,  $\Delta t = 12^\circ\text{C}$  change to  $26^\circ\text{C}$ . If the stimulus was detected,  $\Delta t$  was gradually decreased by  $1^\circ\text{C}$  until either the participant did not perceive a thermal change, or, if every stimulus was detected, all stimuli for that direction and ROC combination were exhausted. Then another ROC and direction were randomly chosen, until all ROC/direction combinations were exhausted. A stimulus presentation comprised of 10 seconds of stimulus followed by a return to the start point and 30 seconds of adaptation at the start point. There were no visual or auditory cues as to when stimuli were presented. Participants were instructed to click the left mouse button as soon as they felt a change in thermal stimulation. At this point, two Likert scales appeared on screen asking the individual to rate the stimulus in terms of intensity and comfort, using the same scales as were used to rate the start point, similar to the approach used by others [1, 2, 9]. Another stimulus was then presented after the 30 seconds of adaptation had completed. If the participant clicked the button before the full 10 seconds of stimulation had passed, the Peltiers were immediately returned to start point and the scale ratings corresponded to the stimulus was recorded. If a stimulus was not detected, the Peltiers were then returned to the start point and the 30 seconds of



**Figure 3:** Average perceived intensity of each start point (Higher = more intense)



**Figure 4:** Detection rate for each magnitude of change

adaptation began, before continuing the experiment with a different ROC/direction combination selected. The skin of the non-dominant hand remained in contact with the stimulator for the duration of each condition.

The independent variables were: 1) ROC, 2) magnitude of change ( $\Delta t$  i.e. how much the temperature changed from the starting point), 3) direction of change and 4) start point. The dependent variables were: 1) stimulus perception (if the thermal stimulus was perceived/detected by the participant), 2) time to perception (how long after initiation that the stimulus was perceived), 3) subjective comfort of stimulus and 4) subjective intensity of stimulus. Effects of magnitude of change and start point were analysed using Friedman tests, while ROC and direction were analysed using Wilcoxon tests, because the data violated normality assumptions. 9 participants (7 Male, 2 Female) aged between 21 and 30 ( $M=26$ , median = 25) took part in the evaluation. All were right-handed, and were paid £20 for participation, which lasted between 2 and 3 hours. The study was conducted in an office environment of 17.8-24.7°C ( $M=21.2$ ,  $SD=1.6$ ) and as such should have a limited impact on perception [1].

## Results

### Start Point

Initial comfort and intensity values for the start points before any other stimuli were presented were compared using a one-way ANOVA. The start point did not influence comfort significantly ( $F_{12,104}=0.825$ ,  $p=0.624$ ). Although the comfort values do not change much, the standard deviations of the reported values get larger as the temperatures move further away from the central temperatures, indicating that away from neutral skin temperature there is much more variability

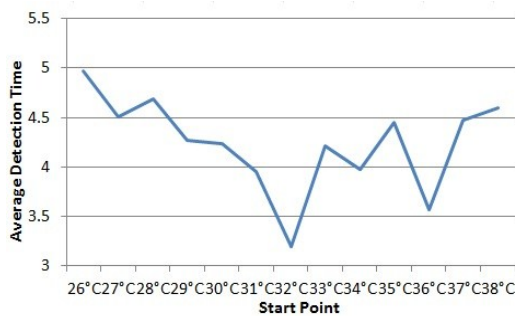
in individuals. Start point had a significant effect on perceived intensity ( $F_{12,104}=6.007$ ,  $p<0.001$ ). As can be seen in Figure 3, in general the warm temperatures were more intense, which matches previous research findings [1, 9], as the warm temperatures were closer to the warm pain threshold than the cool temperatures to the cold pain threshold. Pairwise comparisons were made using adjusted Bonferroni values ( $p=0.0006$ ). Significant differences were found between 38°C and each of 29, 30, 31, 32, 33 and 34°C.

### Detection Rate

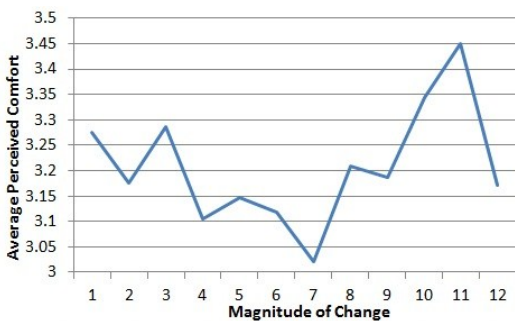
Figure 4 shows the detection rates for the different magnitudes. Magnitude of change had a significant effect on detection rate ( $\chi^2(11)=49.662$ ,  $p<0.001$ ). *Post hoc* Wilcoxon tests with an adjusted alpha ( $p=0.0007$ ) revealed that 1°C changes had significantly lower detection rate than all other magnitudes, apart from 12°C. 2°C changes were also found to be significantly lower than 6°C and 8°C changes. ROC had a significant effect on detection rate ( $Z=1.997$ ,  $p=0.046$ ). The 3°C/sec ROC had a slightly higher detection rate (89.56%) in comparison with the 1°C/sec rate (86.79%). There were no significant effects of either start point ( $\chi^2(12)=20.042$ ,  $p=0.066$ ) or direction of change ( $Z=-0.827$ ,  $p=0.408$ ) on detection rate.

### Time to Detection

For time to detection, magnitude of change did not have a significant effect ( $\chi^2(11)=11.784$ ,  $p=0.380$ ). Start point was found to have a significant effect ( $\chi^2(12)=126.962$ ,  $p<0.001$ ). The general trend, as shown in Figure 5, is that, for the more central temperatures (i.e. close to neutral skin temperature) the detection time is faster and as the start point moves towards the extremes of the range then the



**Figure 5:** Average detection time in seconds from each start point



**Figure 6:** Average perceived comfort for each magnitude of change (lower = more comfortable)

time to detection increases. *Post hoc* Wilcoxon tests with an adjusted alpha ( $p=0.0006$ ) revealed a number of significant differences. 32°C was significantly faster than all other temperatures except 36°C. 33°C was significantly slower than 26°C. 36°C was faster than 26°C, 29°C, 30°C, 33°C, 35°C and 37°C. ROC had a significant effect on time to detection ( $Z=-5.679$   $p<0.001$ ). The higher ROC had a faster detection time ( $M=3.886$   $SD=1.899$ ) than the lower ROC ( $M=4.576$   $SD=2.119$ ). Direction of change had a significant effect ( $Z=-4.527$   $p<0.001$ ), where cool changes ( $M=4.053$   $SD=2.068$ ) were detected more quickly than warm ( $M=4.376$   $SD=1.988$ ).

#### Perceived Comfort

Direction of change significantly affected comfort ( $Z=9.821$ ,  $p<0.001$ ), with cool changes ( $M=2.912$   $SD=1.423$ ) rated as being more comfortable than warm changes ( $M=3.459$   $SD=1.435$ ). ROC also had a significant effect ( $Z=4.781$ ,  $p<0.001$ ) the slower ROC ( $M=3.055$   $SD=1.339$ ) was rated as being more comfortable than the faster ROC ( $M=3.306$   $SD=1.543$ ). Magnitude of change had a significant effect on perceived comfort ( $\chi^2(11)=80.780$   $p<0.001$ ). In general, as shown in Figure 6, comfort increased initially before decreasing as magnitude increased. While the values increase, the average values remain in the comfortable range. This increase and leveling out of comfort values is also borne out in the pairwise comparisons (adjusted alpha  $p=0.0007$ ). A magnitude of change of 1°C ( $M=3.276$   $SD=1.291$ ) was significantly different to 2°C ( $M=3.176$   $SD=1.465$ ), 3°C ( $M=3.286$   $SD=1.496$ ), 4°C ( $M=3.104$   $SD=1.439$ ) and 12°C ( $M=3.171$   $SD=1.524$ ). Significant differences were also found between 3°C and 12°C. Start point also had a significant effect on perceived comfort

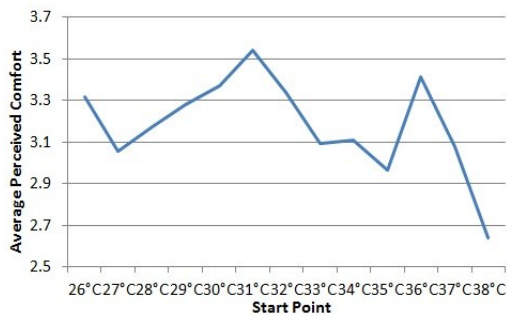
( $\chi^2(12)=50.917$   $p<0.001$ ), the influence can be seen in Figure 7. Pairwise comparisons (adjusted alpha  $p=0.0006$ ) revealed that most of the differences are between 38°C and values in the middle of the start point range (29-32°C) as well as other extreme start points (26-37°C). The difference between 38°C and the other points can mostly be explained by the fact that all changes from 38°C are cool, as has been outlined in this section, and in previous work [1, 2, 9] cool changes are in general more comfortable. The difference between 31°C and 35°C was also significant.

#### Perceived Intensity

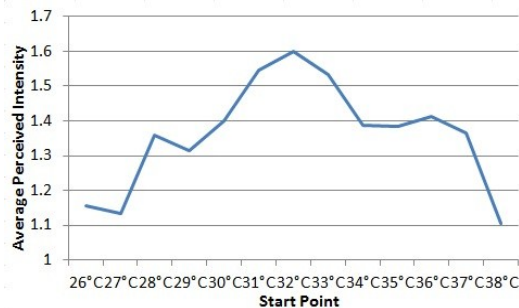
Direction did not have a significant effect on perceived intensity ( $Z=0.388$ ,  $p=0.698$ ). Warm changes ( $M=1.385$   $SD=0.717$ ) were perceived to be as intense as cool changes ( $M=1.371$   $SD=0.699$ ). There was a significant difference between the two ROC ( $Z=-8.302$   $p<0.001$ ). The faster ROC ( $M=1.513$   $SD=0.753$ ) was perceived to be more intense than the slower ROC ( $M=1.229$   $SD=0.622$ ). Magnitude had no significant effect on perceived intensity ( $\chi^2(11)=13.400$   $p=0.268$ ). It should be noted that perceived intensity did increase as the intensity of change increased. Start point had a significant effect on perceived intensity ( $\chi^2(12)=43.144$   $p<0.001$ ), see Figure 8. Pairwise comparisons (adjusted alpha  $p=0.0006$ ) showed differences between 31°C and both 27°C & 38°C; between 32°C and 26°C, 27°C, 29°C and 38°C; between 33°C and 27°C, 38°C; and between 34°C with 38°C.

#### Discussion

From the results we highlight some interesting and important factors that should be considered when designing thermal user interfaces for continuous feedback and also outline future work. Based on our



**Figure 7:** Average perceived comfort for changes from each start point (Lower = more comfortable)



**Figure 8:** Average perceived intensity for changes from each start point (Higher = more intense)

results we would recommend that, for a change to be perceived, a minimum of 3°C should be used, which would give 5 distinct levels within the temperature range we used (26-38°C), for example. Changes should also begin from temperatures of 32°C±4°C, if possible, to maximise stimulus intensity. Also, given that the thermal sense is non-symmetrical and that the cool temperatures were well removed from pain thresholds, it could be possible to extend the temperature range to colder temperatures. Previous research [7] indicated that 2°C differences should be detectable within a 10°C temperature range, although they did not indicate what that range is, and the changes all seemed to be warm relative to neutral skin temperature. While this change could potentially be detected, 3°C would ensure that a change was detected across the temperature range. Wilson *et al.* [9] also found 3°C to be preferable to 1°C, but as they only used 3 different magnitudes of change, they did not have the range of temperature changes that we have for comparison. Our findings also demonstrate that the start point will influence perception of a thermal change. Changes from the central temperatures (i.e. those closer to 32°C neutral skin temperature) felt more comfortable than those at the extremes (i.e. warmer and cooler than neutral). At the same time, they feel more intense in comparison than at the extremes of the temperature range used. This, in conjunction with findings for direction of change, would indicate that, for thermal interfaces to be comfortable, warm changes are preferable from cool starting points and vice versa. The initial results presented here are for evaluations conducted in a relatively stable environment, but other factors such as mobility [9], clothing [2] or the environment [1] might dictate how many levels it is possible or practical to use. These factors will be evaluated in more detail in

future experiments. The initial findings and recommendations will also be used to design a range of thermal widgets e.g. thermal progress bar, thermal contact list etc. The apparatus used in this evaluation can be added to a range of devices from phones [8] to tablets to a mouse [4] to allow the evaluation of thermal widgets and further evaluation of continuous thermal stimulation.

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