The Effect of Clothing on Thermal Feedback Perception

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ABSTRACT

Thermal feedback is a new area of research in HCI. To date, studies investigating thermal feedback for interaction have focused on virtual reality, abstract uses of thermal output or on use in highly controlled lab settings. This paper is one of the first to look at how environmental factors, in our case clothing, might affect user perception of thermal feedback and therefore usability of thermal feedback. We present a study into how well users perceive hot and cold stimuli on the hand, thigh and waist. Evaluations were carried out with cotton and nylon between the thermal stimulators and the skin. Results showed that the presence of clothing requires higher intensity thermal changes for detection but that these changes are more comfortable than direct stimulation on skin.

Categories and Subject Descriptors

H5.2. User Interfaces: Haptic IO.

General Terms

Design, Human Factors.

Keywords

Thermal, haptic, touch, non-visual.

1. INTRODUCTION

Thermal feedback has a number of potential uses in HCI and mobile interaction. It can act as a non-visual notification channel for situations that are too bumpy or noisy for vibrotactile or audio feedback. It can enhance both visual and non-visual feedback by adding extra depth to the interaction experience, e.g. thermal feedback could be used to add affect that is not provided by other modalities [3, 8]. Thermal output is also entirely private; audio may be heard by others, vibrotactile may be heard and felt by others and visual may be seen by others. A great deal of research has looked at the underlying characteristics of human thermal perception [1, 4, 10]; however thermal feedback and interaction is a relatively new area of research [2-3, 8, 11-12]. The majority of this previous work does not take environmental factors, such as ambient temperature, humidity or clothing into account. In addition, many systems that investigate thermal perception assume direct contact with the skin. In an attempt to overcome some of these shortcomings, we investigate one particular environmental factor, namely the presence of clothing. We investigate thermal perception at body locations normally associated with mobile devices, i.e. waist (where the phone might be clipped to a belt) and upper thigh (phone in a trouser pocket) and look at the effect of materials with different thermal properties (nylon and cotton) on perception of thermal cues. The results will help us understand how to construct thermal feedback for a user interface that is usable in a wider range of usage contexts.

2. RELATED WORK

Jones and Berris [5] summarise the "desired features" of a thermal display based on both VR research and psychophysical evidence. They recommend using stimulus temperatures of 22-42°C and using higher rates of change to maximize detection of stimuli. They also suggest a thermal interface should be capable of heating and cooling resolutions of 0.001°C and 0.002°C. Wettach et al. [11] designed a Peltier heat pump-based thermal device for mobile interaction and tested users' ability to differentiate three different stimulus temperatures (32°C, 37°C and 42°C). Initial error rates were approximately 65%, although this figure was reduced to 25% after long-term user training. None of these temperatures would be considered "cool" and so this study suggests that individuals can identify varying degrees of warmth, not simply a change from one temperature to another. Also using Peltier-based thermal feedback, Wilson et al. [12] present two studies looking into how well users could detect different warm and cool stimuli presented to the fingertips, palm, dorsal surface of the forearm and the upper arm. Evaluations were carried out in static and mobile settings. Results showed that the palm is most sensitive, cool is more perceivable and comfortable than warm and that stronger and faster-changing stimuli are more detectable but less comfortable. In this paper we extend the work conducted by both Wettach et al. and Wilson et al. by looking at different body locations and by investigating the effects of clothing on perception.

Other related research investigating thermal feedback has looked at more abstract issues. Gooch [2] found that adding thermal feedback to remote, mediated communication could lead to increased feelings of 'social presence'. Nakashige et al. [8] accompanied photographs of warm and cold scenes with either warm or cold feedback. A small study indicated that the foods appeared more appealing when accompanied by the appropriate temperature. Iwasaki et al. [3] suggest a system that could be used to convey emotional information to another user through augmentation of an existing mobile phone. When investigating preconceptions of meaning/significance associated with thermal sensations, Lee and Lim [7] found that users treat sensations as a continuum and that sensations were almost meaningless without context. They also found that cold stimuli were generally less preferred than warm. Kushiyama et al. [6] developed 'Thermo-pict', using Peltiers it provides patterns of thermal stimulation, including thermal tactile 'pictures' and visible displays. Narumi et al. [9] developed a contextual/ambient thermal display for more mobile scenarios. Although not tested experimentally the latter two examples show some interesting potential uses of thermal interfaces.

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3. EVALUATION

Fifteen participants (10 male, 5 female) aged 22 to 39 (mean=28.87, median=26) took part in this experiment. Most were studying or working at the University. All were right-handed and paid £12 for participation, which lasted just over an hour. We used a custom microcontroller board that could independently drive four Peltier heat pumps [12]. These permit a high level of control over temperature output and also allow for both warming and cooling. Each Peltier device could be independently controlled over USB, with the temperature set anywhere within the temperatures of -20°C to +45°C, accurate to 0.1°C. The Peltiers were bonded to circuit boards with a heatsink bonded to the other side. Safety mechanisms on the board prevented them from becoming hotter than 45°C and cut off all power and input if a thermistor detecting the Peltier output became electrically or physically disconnected. For our study we used two Peltiers; two instead of one gave a larger stimulus area and meant that we would need lower intensity output to produce detectable sensations [10]. No more than two were used as this would have required too large an area of skin for mobile use.

3.1 Stimuli

The thermal stimuli used in this evaluation were the same as those used by Wilson *et al.* [12]. A neutral starting temperature of 32°C was chosen as this is within the defined 'neutral zone' of thermal sensation [5, 10, 12] and has been used in other studies [12]. The skin was adapted to this temperature before each trial session and was returned to it between each stimulus presentation. Two different rates of stimulus change (ROC) were used: 1°C/sec and 3°C/sec. Three different stimulus intensities were used: 1°C, 3°C and 6°C. As thermal perception is bipolar, both warming and cooling stimuli were used. Therefore a single stimulus consisted of warming or cooling at a set intensity (1°C, 3°C or 6°C) at one ROC (1°C/sec or 3°C/sec), for example, warming 3°C at 1°C/sec. These temperatures are well removed from cold and hot pain thresholds. Each stimulus was delivered twice, giving a total of 24 stimuli per session (3 intensities x 2 directions x 2 ROC x 2 presentations).

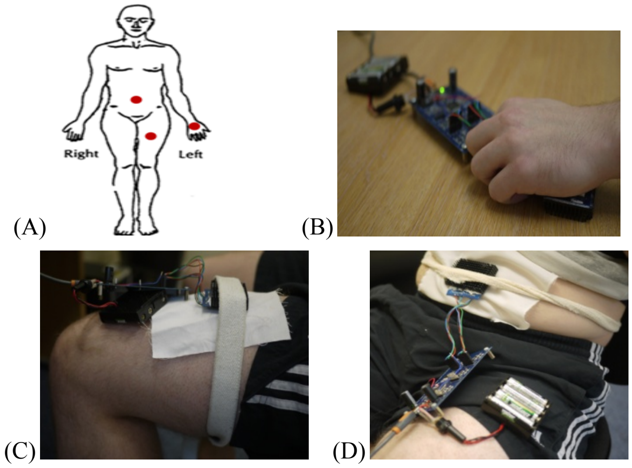

Figure 1: Stimulator sites on the body (A), the thenar with no material (B), the thigh with cotton (C) and waist with nylon (D).

As our interest is in using thermal feedback for mobile interaction and also to investigate the impact of clothing, we selected three body locations that are used to either hold, transport or interact with a mobile device, or locations that a mobile device might be located where clothing would also be present. The thenar eminence (the bulbous region of the palm adjoining the thumb) of the non-dominant hand was chosen as a mobile device would press against it when held in the hand. The upper thigh of the left leg was chosen as this is akin to having a device in a trouser pocket. Finally, the waist was chosen as this would simulate having a device on a belt. Both the waist and the thigh are commonly covered by clothing. Although the thenar is not normally covered by clothes (only when wearing gloves), Wilson et al. [12] found it had the best sensitivity in their study and as such the thenar provided us with a best case to compare against.

To simulate clothing, two different materials were chosen: cotton and nylon. These two materials are both commonly used in clothing and have different thermal properties. Swatches of these materials were placed between the Peltier stimulators and the skin of the participants during experimental sessions. The thermal properties of the materials can be dependent on the thickness of material used, weave, surface area etc. Efforts were taken to make sure that material samples were approximately the same thickness and were the same surface area, just covering the peltiers and heat sinks. To ameliorate some of the potential problems caused by differences in the materials, the two materials have very different thermal properties, cotton[1] has a thermal conductivity of 0.04 W·m−1·K−1 approximately and nylon[2] has a thermal conductivity of 0.25 W·m−1·K−1 approximately.

3.2 Design and Procedure

The design was based on that of Wilson et al. [12]. The task was split into 3 conditions, with participants receiving stimulations at all locations (thenar, waist, thigh) and with all materials (none, cotton, nylon). The order of the location and the material was rotated using a Latin square. The participant was sat at a desk upon which there was a computer monitor and mouse. For the thenar conditions, the Peltier stimulator lay on the desk in front of the seated participant, facing up so that the users could lay their thenar on the stimulator. For the waist and thigh conditions, the stimulator was held against the body with an elastic fabric strip (Figure 1). At the start of each condition the stimulators were set to a neutral starting temperature of 32°C for 2 minutes so as to adapt the skin to this temperature. After the adaptation period, all 24 stimuli were presented in random order. A stimulus presentation comprised of 10 sec. of stimulus followed by a return to the neutral temperature and 30 sec. of adaptation. There were no visual or auditory cues as to when stimuli were presented. Participants were instructed to click the mouse button as soon as they felt a change in thermal stimulation, in any direction and at any intensity. Once this occurred, the time elapsed since the initiation of the stimulus was taken as the time-to-detection. At this point, two 7-point Likert scales appeared on screen asking the participants to rate the stimulus in terms of *intensity* (from "very cold" to "very hot") and *comfort* (from "very uncomfortable" to "very comfortable"), similar to others used before [1, 12]. They then clicked on a submit button and another stimulus was presented after the 30 seconds of adaptation. If the participant clicked the mouse button before the full 10 seconds of stimulation had passed, the Peltiers were immediately returned to neutral and the rating scales were presented. In total a user would receive 72 (24 stimuli * 3 sessions) stimulations over an entire experimental session. As we had 15 participants this resulted in 1080 total potential stimulations. The independent variables were: *Rate of change (ROC), Stimulus intensity, Direc-*

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[1] http://physics.info/conduction/

[2] http://www.engineeringtoolbox.com/thermal-conductivity-d_429.html

tion of change (warm or cool), *Body location* and *Material Present*. The dependent variables were: *Stimulus detection* (if one was perceived), *Detection time* (how long after the initiation of a stimulus that it was detected), *subjective intensity of stimulus* and *subjective comfort of stimulus*.

4. RESULTS

Due to some technical issues with the hardware not all conditions being completed, as a result 932 of the possible 1080 stimulations were submitted to the participants. This was taken into account when calculating all of the results and statistics. For all variables Friedmans analysis of variance of ranks was used to analyse the effect of intensity of change, body location and material on the number of stimuli detected. Wilcoxon T comparisons were used to analyse the effect of direction of change and ROC. Non parametric statistics were utilized as our data did not fit a normal distribution. Environmental temperature can influence skin temperature [5], in particular particularly high (>25°C) or low (<=15°C) environmental temperatures can cause the skin temperature to shift from the neutral zone. As such we recorded room temperature and humidity during each trial and the ambient temperature did not fall outside the range that would cause a shift in skin temperature.

4.1 Number of Detections

Intensity of change was found to have a significant effect on the number of thresholds produced ($\chi2$ (2) =185.009, p<.001). Post hoc Wilcoxon T comparisons showed significant differences between stimulus intensities: 1°C vs. 3°C (T =9842 x p<0.001), 1°C vs. 6°C (T=15910 p<0.001) and 3°C vs. 6°C (T=2242 p<0.001). The number of stimuli detected increased as the intensity increased with means of 19.42%, 58.06% and 70.93% for 1°C, 3°C and 6°C intensities respectively. Location was also found to have a significant effect on the number of changes detected ($\chi2$ (2) =47.03, p<.001). Post hoc Wilcoxon T comparisons showed that the thenar (64.04%) produced more detections that both the waist (T=6930 p<0.001) and the thigh (T=2256 p<0.001), although the number of detections for the waist (45.33%) was high than that of the thigh (38.81%) the difference was not significant. The presence of different materials was also significant ($\chi2$ (2) =52.81, p<.001). Post hoc Wilcoxon T comparisons showed significant differences between all materials: none vs. cotton (T = 1716 p<0.001), none vs. nylon (T=2275.5 p<0.001) and cotton vs. nylon (T=2436 p<0.001). The number of stimuli detected decreased as the thermal conductivity decreased with means of 65.42%, 46.83% and 36.39% for none, nylon and cotton materials respectively. ROC was shown to be significant (T=9576.5 p=0.007) with the higher ROC producing more detections. There was no significant effect of direction.

As well as looking at the number of stimuli detected we also investigated the false detections that were made. There are two types of error; the first is when a participant believed they had felt a change when no change had been submitted and the second is when a user has missed a stimulus but detects the change back to neutral. The thenar as the most sensitive area has the most errors per location (Average 3.6 errors for thenar, average 3.23 errors for waist and average 2.83 errors for thigh). It was also seen that the presence of material increases the number of both types of error made (Average 2.43 errors for none, average 3.3 errors for cotton and average 3.93 errors for nylon). In the majority of cases nylon causes more errors than cotton. Some participants noted that sometimes they felt the device or the material retained some heat, this would explain why nylon with a higher thermal conductivity would cause more errors. If it is the case that some materials retained more heat this could also potentially lead to errors in identifying if a stimulus is warm or cool, this will be investigated in more detail in Section 4.3.

4.2 Time to Detection

Location was found to have a significant effect on the time to detection ($\chi2$ (2) =25.034, p<.001). Post hoc Wilcoxon T comparisons showed that the thigh (median = 4.04sec) produced significantly slower detection times than both the waist (3.4sec) (T=2575 p=0.012) and the thenar (3.29sec) (T=1621 p<0.001), with no significant difference between the thenar and waist. The presence of different materials was also significant ($\chi2$ (2) =46.908, p<.001). Post hoc Wilcoxon T comparisons showed significant differences cotton and the other conditions: none vs. cotton (T=5772 p<0.001) and cotton vs. nylon (T=5884 p<0.001). The time to detection increased as the thermal conductivity decreased with medians of 3.06 sec, 3.3 sec and 4.71 sec for no material, nylon and cotton materials respectively. Direction significantly affected time to detection (T=17263 p<0.001) with cool stimuli (median=3.27sec) being detected more quickly than warm (median=3.84sec). ROC also significantly affected time to detection (T=7050.5 p<0.001) with higher ROC (3°C/sec) producing a significantly lower time to detection (median=3.36) than the lower ROC (1°C/sec; median=3.36sec). Intensity did not have an effect.

4.3 Subjective Stimulus Intensity

As was noted in Section 4.1 some users noted that they felt it difficult to distinguish between warm and cold stimuli when materials were placed between the skin and the Peltier stimulator. Users were asked to rate stimuli on a seven point scale from very hot (0) to very cold (6). These ratings were used to measure errors e.g. warm being perceived as cold. In total 26 errors were made, of those more were for hot (17) than cold (9) and more of these occurred with no material being present (12) than with cotton (6) or nylon (8) being present. As it did not appear that the participants made as many errors as they believed, the 0-6 scales were mapped to intensity scales of 0 – 3, with 0 being neutral and 3 being very intense. Intensity had a significant effect on perceived intensity ($\chi2$ (2) =28.826, p<.001). Post hoc Wilcoxon T comparisons showed the higher intensity changes to be different from the other two stimulus intensities: 1°C vs. 6°C (T=533 p<0.001) and 3°C vs. 6°C (T=1037.5 p<0.001). The perceived intensity increased as the intensity increased 1°C (mean=1.071 median=1), 3°C (mean=1.295 median=1) and 6°C (mean=1.716 median=1) intensities respectively. Direction significantly affected perceived intensity (T=2410 p=0.015) with cool stimuli (mean=1.549 median=1) being more intense than warm (mean=1.392 median=1). ROC also significantly affected intensity (T=4693.5 p<0.001) with the lower ROC (1°C/sec) being less intense (mean=1.253 median=1) than the higher ROC (3°C/sec; mean=1.646 median=1). Location and the presence of material were found to not have an effect.

4.4 Subjective Stimulus Comfort

Subjective stimulus comfort was measured on a seven point scale from very comfortable (0) to very uncomfortable (6). Intensity of change was found to have a significant effect on the perceived comfort of stimuli ($\chi2$ (2) =14.385, p<.001). Post hoc Wilcoxon T comparisons showed the higher intensity changes to be different from the other two stimulus intensities: 1°C vs. 6°C (T=1063 p<0.001) and 3°C vs. 6°C (T=3287 p<0.001). The perceived comfort decreased as the intensity increased 1°C (mean=1.649 median=1), 3°C (mean=2 median=2) and 6°C (mean=2.425 median=2) intensities respectively. The presence of different materials was also significant ($\chi2$ (2) =11.164, p=.004). Post hoc Wilcoxon T comparisons showed that the presence of cotton (mean=1 median=1.769) resulted in participants feeling significantly more comfortable than with no material (mean=2.522 median=2). While nylon was found to be more comfortable than no material (mean=1.946 median=1) there was no significant difference between it and either no material or cotton. However it can be seen that comfort increases as thermal conductivity decreases. Direction significantly affected perceived comfort (T=6001 p<0.035) with warm stimuli (mean=2.013 median=2) being more comfortable than cool (mean=2.311 median=2). ROC also significantly affected comfort (T=6707 p=0.021) with the lower ROC (1°C/sec) being more comfortable (mean=1.995 median=2) than the higher ROC (3°C/sec; mean=2.296 median=2). Location was found to not have an effect. It should be noted that the mean and medians of all variables were in the comfortable range.

5. DISCUSSION AND CONCLUSIONS

Based on the results in this paper there are several new, interesting and important factors that should be considered when designing thermal feedback both in general and for mobile devices.

While the thenar eminence is the optimal location for feedback, the waist is suitable. In measures of 'number of stimuli detected' and 'time-to-detection' the thenar eminence was shown to be the most sensitive area. Although the waist suffered lower overall detection rates, it had similar time to detection. All three locations had similar perceived comfort and intensity ratings.

Different materials result in different design recommendations for thermal feedback. Materials with lower thermal conductivity require more intense changes; the required changes in intensity are lower for materials with higher thermal conductivity, although materials with higher thermal conductivity do not affect time to detection significantly. Materials with higher thermal conductivity can also result in more errors than those with lower thermal conductivity.

Materials mean that it should be possible to use higher intensity changes. While participants perceived stimuli delivered when materials were present to be as intense as direct contact with the skin, they perceived higher intensity changes to be more comfortable than when the stimulators are directly in contact with the skin. This may allow more intense changes to be used, and indeed if lower intensity changes cannot be detected then these are necessary. It should also be noted that although not supported in the results that some users stated that they found it difficult to identify changes as sometimes the material appeared to retain heat, this may mean that care should be taken to not present stimuli in rapid succession.

It is not clear if warm or cold changes are "better". Wilson et al. [12] put forward that cold changes were "better", in contrast in the study by Lee and Lim [7] warms changes were perceived to be "better". Our study used similar apparatus to Wilson et al, and in contrast to their findings we found that with the presence of material that cool changes were perceived as more intense, warm changes were more comfortable. However both studies did find that cool stimuli were detected more quickly than hot. It may be a case that the "dulling" effect of material on intensity makes warms changes more acceptable to users, but more research is required to investigate which, if any, direction is more useable and acceptable.

In conclusion, this paper has presented a user study which investigated how well users were able to detect warm and cold stimuli presented to three body locations and the effect of different clothing material on user's ability to detect those changes. Simple guidelines for design of feedback based on our results are outlined, with a view to identifying features of stimulus presentation that are impacted by the presence of clothing.

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