Thermal Icons: Evaluating Structured Thermal Feedback for Mobile Interaction

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ABSTRACT

This paper expands the repertoire of non-visual feedback for mobile interaction, established through Earcons and Tactons, by designing structured thermal cues for conveying information. Research into the use of thermal feedback for HCI has not looked beyond basic 'yes-no' detection of stimuli to the unique identification of those stimuli. We first designed thermal icons that varied along two parameters to convey two pieces of information. We also designed intramodal tactile icons, combining one thermal and one vibrotactile parameter, to test perception of different tactile cues and so evaluate the possibility of augmenting vibrotactile displays with thermal feedback. Thermal icons were identified with 82.8% accuracy, while intramodal icons had 96.9% accuracy, suggesting thermal icons are a viable means of conveying information in mobile HCI, for when audio and/or vibrotactile feedback is not suitable or desired.

Author Keywords

Thermal feedback; mobile interaction; non-visual feedback.

ACM Classification Keywords

H.5.2 User Interfaces: Haptic IO

INTRODUCTION

The small and cramped GUIs of mobile phones have motivated the design of non-visual cues to display information and free visual attention. Examples include Earcons [1, 2] and Tactons [3], structured auditory or vibrotactile stimuli that can convey two or three pieces of information to the user, mapped to the icon's structural parameters such as rhythm or timbre/roughness. Thermal stimulation is a rich, emotive and entirely silent information source, which could be used as an alternative mobile feedback channel when required, as it is silent for quiet environments and potentially more salient for bumpy environments. It may also provide hedonic meaning not necessarily present in vibrotactile patterns [8]. While we have a finely tuned thermal sense in terms of detecting changes, it is yet to be fully established whether identification of unique thermal stimuli is possible and if they can be used in mobile HCI to convey information. It is also possible that thermal feedback could be used to augment existing vibrotactile feedback, either replacing less distinct or feasible Tacton parameters (such as spatial location) or by adding an extra thermal parameter to vibrotactile feedback.

Therefore, we tested the identification of specific forms of thermal stimulation. Following in the footsteps of Tactons we began with two parameters, *direction of change* (warm and cool) and *subjective intensity of change* (moderate and strong) in order to convey the Source ("Personal" and "Work") and Importance ("Standard" and "Important") of a message. In a separate condition, we also used one thermal parameter (*direction of change*) and one vibrotactile parameter (*rhythm*) together to convey the same information. The purpose was to test interpretation of two different tactile feedback channels simultaneously, to judge if thermal feedback could successfully augment or replace Tacton parameters. We use the term 'intramodal' to refer to this use of two channels (vibration and thermal) of the same modality (tactile), in contrast to 'bimodal', which refers to the use of more than one modality (e.g. tactile + audio). The research described in this paper was conducted with participants sat indoors and so serves as an initial baseline investigation.

BACKGROUND

Audio and Tactile Icons

Earcons [2] are structured, abstract non-speech sounds used to convey information about an interface non-visually. Information is encoded in the sound's auditory parameters, such as the timbre, rhythm and pitch. In this way a single Earcon can convey up to three pieces of information [2]. Using Earcon design as a basis, Brown *et al.* [3] developed Tactons to convey information through vibrotactile stimulation of the skin. Manipulating the rhythm and roughness parameters of Tactons provides reliable identification of two pieces of information, with spatial location providing a potential third parameter.

Because some environments are not suitable for audio or tactile feedback, and because user preference varies regarding which modality is desirable when, Hoggan and colleagues developed crossmodal audio and tactile icons which

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can be interchanged to suit the user's current environment or preference [6]. While vibrotactile feedback is commonly used for private notifications, it is not entirely private, as the vibration is often audible to, or even felt by, others. Thermal icons could provide an entirely silent means of conveying information, or provide a replacement parameter for less reliable (e.g. roughness) or less feasible (spatial location) Tacton parameters [3].

Thermal Perception

There are myriad influences on thermal perception; only those most relevant to the current study are included here. Thermal perception can be highly precise, with experts able to detect changes less than 0.2°C above/below skin temperature in ideal laboratory conditions [9]. The skin sits at a neutral temperature of 30-36°C, depending on the individual [7]. Detection of changes within this range is dependent more on the rate of change (ROC) of the stimulus than the actual extent of the change itself [8]. Faster changes feel stronger and are felt sooner than slow changes. Outside of this range, we become more sensitive to changes that move further away from neutrality towards the pain threshold [8].

Thermal HCI

Wettach *et al*. [10] designed a Peltier-based thermal feedback device for mobile interaction and tested users' abilities to differentiate three different stimulus temperatures (32°C, 37°C and 42°C). Error rates remained at 25% even after long-term training. None of these temperatures would be considered 'cool', so although the error rate was relatively high, this study suggests that individuals may be able to identify absolute degrees of warmth, given the right stimuli. Wilson *et al*. [12] tested the effects of various factors on detection rates of stimuli as well as subjective perceptions of the stimuli (intensity and comfort). They found that the Thenar eminence (bulbous area of palm adjoining the thumb) was the most sensitive location, cold stimuli were easier and faster to detect and that manipulating both the extent of thermal change (Wilson *et al.* use the term "intensity") as well as the ROC created different subjective intensity ratings. Therefore, subjective stimulus intensity is not solely based on the extent that the stimulator changes from skin temperature. For example, the same extent of change (e.g. 6°C) felt subjectively less intense when warmed or cooled at the slower ROC of 1°C/sec, compared to the faster 3°C/sec. This suggests that manipulating both extent of change and ROC can create perceptually distinct stimuli.

EVALUATION

We used an updated design of the hardware used by Wilson *et al.* [12], with ours shown in Figure 1. The same Peltier module was used, but it was attached to a larger heat sink for more effective heat dissipation. The Peltiers connected to a MacBook Pro running Windows 7 via a Bluetooth microcontroller and were powered by 4xAA batteries. For the vibrotactile feedback, an EAI C2 Tactor was used (www.eaiinfo.com), which converts audio files to vibration. This is the same device used in other Tacton research [3]. The task closely resembled that used by Brown *et al.* [3] for identifying multidimensional Tactons. Four thermal icons and four intramodal thermal + vibrotactile icons were used to represent the arrival of four different text/email message types. The messages varied along two dimensions: message Source and message Importance. The Source was either "Personal" or "Work", and the Importance either "Standard" or "Important", giving Standard Personal, Important Personal, Standard Work and Important Work messages.

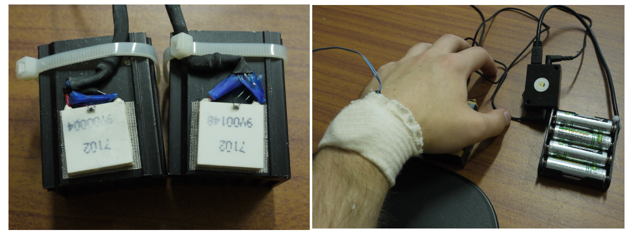

Figure 1: Peltier modules used to produce thermal stimuli (left); experiment apparatus with Peltiers under palm (right).

Thermal Icon Design

The design of the thermal icons was guided by the recommendations in Wilson *et al*. [12]. Because the icons are intended for use in mobile HCI, we also took into account the effects of mobility [12] and outdoor environments [5] to choose stimuli that should be perceivable in mobile situations. We chose two of the most salient parameters of thermal stimulation to create the thermal icons: *direction of thermal change* and *subjective intensity of change*. Each of these had two levels: 'warming' and 'cooling' for *direction of change* and 'moderate' and 'strong' for *subjective intensity*, giving four thermal icons: Moderate Warmth, Strong Warmth, Moderate Cooling and Strong Cooling. The mappings between icon and message type are shown in Table 1. For *direction of Change* we began at a neutral skin temperature of 32°C [7], warming and cooling from there. Warmth was chosen to represent personal messages, as there is evidence of an innate association between physical warmth and interpersonal warmth/trust [11]. Work messages are an alternative to personal messages and so were mapped to cold changes. More important messages were mapped to subjectively stronger changes as they are more attention-grabbing [8].

	Thermal	Intramodal
"Source" Parameter	*Direction of Change*	*Direction of Change*
Personal	Warm	Warm
Work	Cool	Cool
"Importance" Parameter	*Subjective Intensity*	*Tactile Rhythm*
Standard	Moderate	Slow Rhythm
Important	Strong	Fast Rhythm

Table 1: Mappings of thermal and tactile parameters to Source and Importance of a message.

Wilson *et al.* [12] used the term "intensity" to refer to the number of degrees by which the stimulator changed from 32°C neutral. To avoid confusion with the *subjective intensity* parameter, we use the term "extent of change" here instead. Therefore, the *subjective intensity* parameter used two extents of change which have received different subjective intensity ratings [12]: 3°C and 6°C (warming to 35°C and 38°C and cooling to 29°C and 26°C respectively). To make the two extents more perceptually different, we used a slow ROC (1°C/sec) for the 3°C changes and a fast ROC (3°C/sec) for the 6°C changes. We avoided smaller changes in temperature, as these are far less likely to be detected, especially when walking [12] or when outdoors [5].

Intramodal Icon Design

The thermal parameter chosen was *direction of change* as it is particularly salient, while the vibrotactile parameter chosen was *rhythm* as this is one of the most easily identifiable parameters of Tactons [3]. Again we used warming and cooling for the two levels of *direction*, in this case warming or cooling by 6°C at 3°C/sec, the large extent of change from the thermal icons. As identification of different vibrotactile rhythms is easier when they contain different numbers of notes [3], we used two 3-second rhythms, one "slow" with three long notes and one "fast" with nine short notes. The *rhythms* are shown in musical notation in Figure 2. The four intramodal icons were: warming + slow rhythm, warming + fast rhythm, cooling + slow rhythm, cooling + fast rhythm. The mappings to message type are shown in Table 1. Rhythms lasted 3 seconds, as this length of time was required to reach the full extent of warming/cooling. We were interested in how well the thermal and vibrotactile stimuli could be processed when presented simultaneously, as skin temperature influences vibrotactile perception [4].

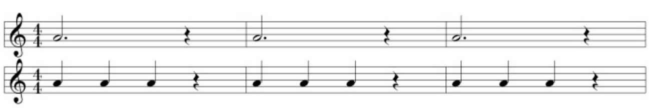

Figure 2: Slow (top) & fast (bottom) Intramodal icon rhythms.

Design & Procedure

Twelve participants took part (7 male, 5 female), aged from 18 to 43 (mean 25.08). All were from within the University and were paid £6 for participation. The evaluation had two conditions: one identifying thermal icons (Thermal condition) and one identifying intramodal thermal+vibrotactile icons (Intramodal condition). The procedure was the same for both conditions and participants took part in both, with the order counterbalanced. The Thenar eminence/lower palm was chosen as the site for thermal stimuli as it is highly sensitive [12] and directly contacts a mobile device held in the hand. Participants laid the palm of the non-dominant hand on top of two Peltiers, with the arm supported by a padded rest (see Figure 1), while the other hand operated a PC mouse. During the Intramodal condition, they also had the C2 contacting with the top of the non-dominant wrist, secured by an elastic strap (white band in Figure 1). Although it was important to present both stimuli (thermal and tactile) at the same location (mimicking presentation from the mobile device itself), it was not feasible in this case to have both presented to the palm, due to the size and placement of the Peltiers.

Both conditions started with adaptation of the palm to 32°C, by resting the palm on the Peltiers for 60 sec. Participants first completed a 10-minute training session where they could feel each icon several times. During this time, four buttons were shown on the PC screen corresponding to each of the four message types. When clicked, the corresponding icon feedback was produced, and participants had to learn to associate the feedback with the message type. In both conditions, the Peltiers changed to the relevant temperature and remained there for 10 sec, before returning to 32°C for 30 sec. In the Intramodal condition, the tactile rhythm and thermal change began simultaneously. Headphones were worn so the vibrations were inaudible.

For the full task, all four stimuli/message types were presented four times in a random order, giving 16 icons per condition. The same four button interface screen was shown as soon as the icon was initiated and the participants were asked to click the button corresponding to which message type they interpreted the icon as representing. As soon as a button was clicked, the Peltiers were returned to 32°C for 30 seconds, after which the next random icon was presented. This repeated until all icons were judged four times. The dependent variables were: *accuracy* (whether the right message type was identified) and *identification time* (IDT, the time taken to choose a message type). IDT indicates the time required to become confident in identifying an icon.

RESULTS

The overall mean accuracy for two-parameter thermal icons was 82.8% (SD=37.8). Mean accuracy for the two thermal parameters individually was 85.4% for *subjective intensity* and 97.4% for *direction of change*. The confusion matrix for thermal icons is shown in Table 2. The median IDT for each Thermal icon was 5.40s, 5.34s, 5.61s and 4.29s for the moderate warm, strong warm, moderate cool and strong cool icons respectively. A Friedman's analysis of the data indicated a significant effect of icon on IDT ($\chi^2(3)=11.075$, $p<.05$), with the two cool icons being significantly different from each other (Wilcoxon $T=854$, $p=0.006$) with an adjusted alpha (p-value) of 0.008.

		Perceived Icon			
		Mod Warm	Strong Warm	Mod Cool	Strong Cool
Actual Icon	Mod Warm	46	1	1	0
	Strong Warm	11	35	1	1
	Mod Cool	0	1	38	9
	Strong Cool	0	1	7	40

Table 2: Thermal Icons confusion matrix: the icons presented and the number of each icon they were perceived as.

The overall mean accuracy for two-parameter Intramodal icons was 96.9% (SD=17.4). Mean accuracy for the two Intramodal parameters was 97.4% for *rhythm* and 99.5% for *direction of change*. A Wilcoxon *T* test showed that participants identified significantly more Intramodal icons than Thermal icons ($T=558.0$, $p<0.001$). The median IDT for each Intramodal icon was 4.12s, 3.77s, 3.63s and 3.91s for the warm+slow, warm+fast, cool+slow and cool+fast icons respectively. A Friedman's test indicated a significant effect of icon on IDT (χ^2 (3)=11.275, p=0.01), but no Wilcoxon *T* tests reached the adjusted level of significance (p=0.008).

DISCUSSION AND CONCLUSIONS

The mean identification rate for thermal icons is high, with 82.9% accuracy in identifying two pieces of information, suggesting thermal icons are a promising method of conveying information. This figure is higher than the 71% identification rate for two-parameter Tactons [3], although we only used two levels per parameter and Brown *et al.* used three. While the results are promising, future revisions should address the slightly more error-prone parameter of *subjective intensity (SI)*. Of the 33 errors, 28 confused the *SI* of the icon, resulting in 85% accuracy for that parameter. The other 5 (of 33) errors confused warm for cold or *vice versa*, giving *direction of change* a much higher accuracy of 97%.

As seen in Table 2, a roughly equal number of *SI* errors occurred within both warming (12) and cooling (16), however the pattern of confusion was different. All but 1 of the warm confusions felt subjectively less intense than was intended (i.e. Important Personal was interpreted as Standard Personal). In contrast, roughly equal numbers of cold confusions were perceived as less (7) or more (9) intense than intended. Participants reported believing that either they became "less sensitive" to changes over time or simply that the stimuli became harder to differentiate. Looking at the frequency of errors over the course of the Thermal condition showed no pattern of increasing error with time so, even if the ability to identify the *SI* depreciated, it did not do so enough to make them indistinguishable. However, given the frequency of such comments, it will be necessary to test this temporal effect on perception fully. One way of increasing the subjective difference between stimuli would be to decrease the extent of change of the moderate warmth/cold and increase the extent of strong cold. Increasing the strong warmth may move too close to the pain threshold, so this is not recommended.

The intramodal icons had a significantly higher mean identification rate than the thermal icons, at 97%, with 99% accuracy for *direction of change* and 97% accuracy for *rhythm*, a figure similar to rhythm identification in Tactons (96.9%) [3]. Therefore, presenting thermal and vibrotactile stimuli together does not appear to significantly hinder interpretation of either, and so thermal changes may be a useful addition to Tactons.

The identification time (IDT) of thermal icons showed that, in line with previous research [5, 12], the coldest icon (strong cool/Important Work) was the fastest to be identified, but only compared to the moderate cool, otherwise the times were comparable. However, overall the IDT were quite high, at 5-6 seconds. Because the two *subjective intensities* varied in their rate of change, they took different lengths of time to reach their extents. Participants may have waited a length of time to see how far the Peltiers changed temperature. In contrast, the amount of thermal change was irrelevant in the intramodal icons, and so identification was 1-2 seconds faster than thermal.

This paper has presented the first examination of thermal icon design and identification, as well as the first study of intramodal thermal+vibrotactile presentation. Results from both are encouraging, as identifying two pieces of information from thermal icons was easy and could be improved with adjusted designs. Presenting two different tactile stimuli simultaneously does not seem to produce confusion. While a necessary next step is testing identification while the user is walking and in outdoor environments, these initial results show thermal icons to be similarly effective in conveying information as Earcons and Tactons.

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