Thermal Feedback Identification in a Mobile Environment

Graham Wilson[1], Stephen Brewster[1], Martin Halvey[2] & Stephen Hughes[3]

[1]School of Computing Science, University of Glasgow, G12 8QQ, UK
[2]Glasgow Caledonian University, Glasgow, G4 0BA, UK
`first.last@{`[1]`glasgow.ac.uk;` [2]`gcu.ac.uk},` [3]`stephenahughes@gmail.com`

Abstract: Audio and vibrotactile feedback are not always suitable or desirable, as noise and/or movement may mask them, and so thermal feedback may provide a salient alternative. In this paper, the identification of 'thermal icons' (structured thermal feedback) was tested as a means of conveying information when users were sitting and walking in an outdoor location. Overall identification rate for thermal icons was 64.6%, but identification of individual parameters was promising, at 94% accuracy for *direction of thermal change* (warming/cooling) and 73.1% accuracy for *subjective intensity* (moderate/strong). Results showed that walking outdoors did not significantly worsen icon identification compared to sitting outdoors, but the environmental temperature had a strong influence. Recommendations are given on how better to design and adapt thermal feedback for use in outdoor mobile scenarios.

Keywords. Thermal feedback; mobile interaction; non-visual feedback.

1 Introduction

Conveying information non-visually is important for mobile interaction, so that visual attention can be paid to the environment. Both Earcons [1] and Tactons [2] have been shown to be effective in conveying information in mobile scenarios. However, there are mobile environments in which audio and vibrotactile feedback may not be suitable, such as very loud (e.g., rock concerts) or very quiet places (e.g., libraries or religious buildings) for audio, or simultaneously loud and bumpy environments, such as public transport, that are unsuitable for both [7]. Thermal feedback is entirely silent and so may be suitable for quiet environments. It could also be more salient in bumpy environments. Further, user preference for when a feedback modality is desired varies by location and situation [7] and thermal feedback may provide a third alternative to audio and vibrotactile feedback. Thermal feedback is an under-studied aspect of touch and so warrants further investigation into potential uses and benefits.

HCI research has measured 'yes/no' detection and subjective comfort/intensity ratings of thermal stimuli in indoor [20] and outdoor [5] environments. However, this research only looked at whether any changes were felt, and not absolute identification of the unique form of those changes (as has been done with Earcons [1] and Tactons

[2]). There is an important difference between simply acknowledging a change in stimulation and being able to uniquely identify specific forms and decode the meaning of them. For thermal feedback to be a viable information source, users must be able to identify unique forms of thermal stimulation. Previously [19], we developed two-dimensional structured 'thermal icons', which could be identified with 83% accuracy, however, the participants in this study were sat indoors. Both walking [20] and environmental temperatures [6, 15] significantly influence thermal perception, so it was necessary to test identification of thermal icons when the user is sitting and walking outdoors, to judge the feasibility of thermal feedback for more realistic mobile interaction. As such, this paper reports an experiment that tested identification of two-parameter thermal icons presented to the palm of the hand from a mobile device when the user was both sitting and walking in an open-air, outdoor environment. Ambient temperature and humidity were measured to study potential environmental influences.

2 Related work

A distinction is made here between perception and identification of thermal stimuli. *Perception* of thermal changes – moving from no sensation to the production of a sensation – is well understood and involves simply acknowledging a change has occurred. However, *identification* of thermal changes – classifying unique forms of encoded stimuli and using those to convey information – is not well understood.

Thermal *perception* can be highly precise, with experts able to detect changes of < 0.2°C from skin temperature in ideal laboratory conditions [14]. The skin naturally rests at a neutral temperature of between 26°C and 36°C in moderate environmental temperatures [9, 13]. 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 [13]. Faster changes feel stronger and are felt sooner than slow changes. Cold perception is generally faster [11, 20] and more precise [10] than warmth perception. Cold or warm environments have the effect of cooling or warming the skin, respectively [6, 15] and we become more sensitive to changes that move further away from neutrality towards the pain thresholds [13]. The thermal sense is not a good "thermometer": it is not good at identifying specific temperatures, as it is based on changes in the overall magnitude of sensation, which translates into a subjective appraisal of the intensity.

Wettach *et al.* [17] trained users to uniquely *identify* five different degrees of warmth at up to 75% accuracy after several days of training. They also report the use of five temperatures to indicate the correct direction of travel in an outdoor navigation task, but few details about the hardware, experimental design or results are given. Exactly what temperatures were used, and so how different they were from each other, was not reported. Other research has attempted to communicate affective information thermally. Suhonen *et al.* [16] studied how thermal feedback was used to convey emotions during remote communication and found that warmth was used to represent or reinforce agreement/positivity, while cold represented disagreement/negativity. However, they did not examine user responses to varying extents of warmth/cold, or their identification of those extents. Iwasaki *et al.* [8] suggested conveying emotional state using warmth on a mobile device, but did not test feedback perception. Emotional responses to thermal stimuli have also been measured by Salminen *et al.* [12] and Halvey *et al.* [4], but only subjective perception of stimuli was measured, not identification. Only Wettach *et al.* [17] had users in a mobile setting, and the paper provides no details on how well the stimuli could be differentiated.

Wilson *et al.* [20] measured *perception* and subjective comfort/intensity ratings of various thermal stimuli for use in HCI when the user was sitting and walking indoors. They found that walking significantly reduced the number of stimuli detected. Halvey *et al.* [5] found that outdoor environmental temperatures also influenced perception of stimuli, with particularly low and high temperatures leading to poorer perception/detection, but only tested perception when sitting. Based on these results, we previously designed and tested *identification* of two-dimensional 'thermal icons' which could convey information during mobile interaction [19]. This structured thermal icon design has the advantage of being capable of conveying two pieces of information. We used two thermal parameters: direction of change (warming and cooling) and subjective intensity of change (moderate and strong) to create four icons conveying the "Source" (Personal or Work) and "Importance" (Standard and Important) of a received text message. Users in this study were able to uniquely identify the two pieces of information with an accuracy of 82.8%, but did so sitting indoors.

Thermal feedback is promising, as it is a truly private feedback method, while vibrations can still be heard or felt by those nearby (for example, sitting on the same bench). It provides unique sensations and is also inherently hedonic [13]. However, if thermal feedback is to be considered a useful alternative means of conveying information in mobile interaction, absolute identification of unique, coded forms of thermal stimulation must be tested in realistic outdoor environments. Currently only *perception* of thermal changes has been tested outdoors and only when the individual was sitting. Therefore, we ran a study testing identification of two-dimensional thermal icons using compact hardware when the participants sat on a bench and walked a route in an open-air outdoor environment.

Fig. 1. Peltier modules used to produce thermal icons (left); attached to back of mobile (right).

3 Evaluation

The apparatus was built by SAMH Engineering and consisted of two Peltier modules, each attached to a heat sink for heat dissipation (see Figure 1, left). The Peltiers were controlled (with ~0.1°C accuracy) by a small microcontroller, powered by four

AA batteries. Custom software on a Nexus One Android device (see Figure 1, right) communicated with the microcontroller over Bluetooth. The Peltiers and heat sinks were attached to the back of the Nexus One, in a position to make contact with the palm of the left hand, which held the device. Both the microcontroller and the battery pack were placed in a small shoulder bag that the participant carried (Figure 2). The apparatus was entirely silent: the Peltiers made no audible sounds when in operation.

3.1 Thermal Icons

The thermal icons were designed to convey two pieces of information: the "Source" and "Importance" of a hypothetical text message. The Source could be either "Personal" or "Work" and the Importance could be either "Standard" or "Important". This gave four different message types: Standard Personal, Important Personal, Standard Work and Important Work. The thermal icons were created in our previous research [19], based on thermal perception when sitting and walking indoors [20] and sitting outdoors [5]. Two salient parameters of thermal stimulation were used to create the 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.

A starting neutral skin temperature of 32°C was chosen, as it sits within the skin's resting thermal range [9] and stimuli warmed and cooled from there. Warmth represented Personal messages, as there is evidence of an innate association between physical warmth and interpersonal warmth or trust [18]. Work messages are an alternative to personal messages and so were mapped to cool changes. More important messages were mapped to subjectively stronger changes as they are more attention-grabbing [13]. Both the extent of thermal change (Δ temperature from skin temperature) and the rate of temperature changes (ROC) influence the perceived magnitude of sensation [20]. Therefore, the two *subjective intensity* levels of 'Moderate' (Standard) and 'Strong' (Important) were created by mixing both Δ temperature change and ROC. Changing temperature by 3°C at 1°C/sec produced the 'Moderate' intensity and changing by 6°C at 3°C/sec produced the 'Strong' intensity [20]. These Δ and ROC values were chosen based on stimuli that produced detectable sensations in previous research [20], as smaller Δ values were less likely to be detected outdoors [5]. These changes were in both *directions*, starting from 32°C, giving thermal icons of:

- Strong Cooling 6°C @ 3°C/sec, to 26°C: Important Work message
- Moderate Cooling 3°C @ 1°C/sec, to 29°C: Standard Work message
- Moderate Warmth 3°C @ 1°C/sec, to 35°C: Standard Personal message
- Strong Warmth 6°C @ 3°C/sec, to 38°C: Important Personal message

3.2 Design & Procedure

Thirteen participants took part (2 female), aged from 22 to 31 (mean 25.6), and were paid £6 for participation. The evaluation had a within-subjects design, with Mobility (sitting, walking) as a factor. The experiment was conducted in an enclosed courtyard adjacent to a university building. There were benches to test icon identification when sitting outdoors, and large, flat concrete paths to test identification when walking outdoors. The area was quiet, away from road traffic, but there was a degree of footfall from students, staff and tourists. A nearby indoor area was used for instruction and training, so that icons could be learnt in a thermally stable environment.

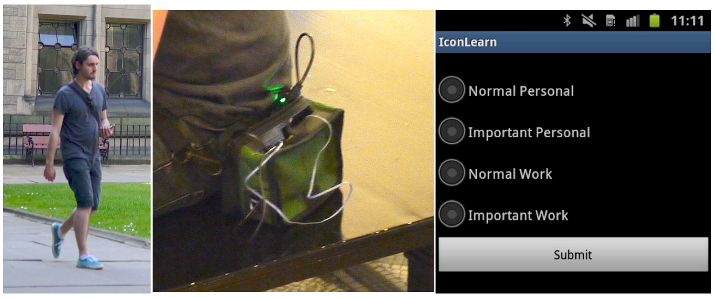

Fig. 2. Participant walking in the courtyard (left), carry bag (centre) and task GUI (right).

The procedure was the same for the sitting and walking conditions and participants took part in both, in a counterbalanced order. The task started with a 10-minute training session seated in the indoor location. First, the mapping of feedback parameters to message types was explained. The training session started with 60 seconds of skin "adaptation", where the Peltiers were set to the neutral starting temperature of 32°C and held in the hand, to equalize skin and Peltier temperatures. The participants were then given 10 minutes to feel each thermal icon as many times as desired and learn the mapping of icon to message type. Training software on the Nexus One showed four radio buttons, each labeled with one of the message types (Figure 2, right). After training, all participants expressed confidence in having memorized the mappings. The participants then took part in the first mobility condition, followed by the second.

In both conditions, the Nexus One was held in the left hand and input was given by the right. The palm of the hand was chosen for stimulation as it is the most sensitive area [14, 20], but other locations may also be suitable such as the wrist/forearm and upper arm [20], where a watch or exercise arm band, augmented with thermal elements, could be worn. During the sitting condition, participants simply sat on the bench. During the walking conditions, participants were asked to walk in a simple square route around the courtyard at their normal walking pace (Figure 2). During both conditions, each icon was presented four times in a random order, with a 30 second gap between subsequent presentations, where the Peltiers were returned to 32°C. The device screen showed the same radio buttons as during training. Participants were instructed, whenever they identified an icon, to press on the radio button corresponding to the interpreted message type, and press "Submit". The Peltiers were immediately set back to 32°C, the user response was recorded and another icon was presented at random after 30 seconds. If the system received no input within 20 seconds of an icon being presented, a "missed" event was logged, and a different icon was presented.

The Independent Variables were *Mobility* (sitting and walking) and *Icon* (four icons). The Dependent Variables were: *Accuracy* (whether the right message type was identified) and *Identification Time* (the time between the start of an Icon presentation and when a response was recorded by the "Submit" button). For overall Accuracy, both pieces of information had to be correctly identified. Accuracy rates for both parameters individually were also recorded and "missed" events counted as an error in all three Accuracy measures. Environmental temperature and humidity were both recorded throughout the study using a thermometer.

4 Results

Influence of Ambient Temperature & Humidity. The mean temperature across all conditions was 20.27°C (SD = 3.99; min = 12.7°C, max = 27.4°C). The potential relationship between environmental Temperature and Accuracy was investigated using Pearson's product-moment correlation coefficient. A significant negative correlation was found between Temperature and Accuracy (r (23) = -.562, $p<0.01$), with Accuracy decreasing as Temperature increased. Humidity had a significant negative correlation with Temperature (r (22) = -.872, $p<0.01$). Humidity ranged from 46.6% to 87.1%, with a mean of 64.22% (SD = 9.29). There was a positive but non-significant relationship between Humidity and Accuracy (r (23) = .381, $p>0.05$).

	Perceived As				
	Mod Warm	**Strong Warm**	**Mod Cool**	**Strong Cool**	**Missed**
Mod Warm	70	10	3	1	10
Strong Warm	31	57	1	3	2
Mod Cool	0	3	54	33	4
Strong Cool	2	1	27	62	2

Table 1. Thermal Icon confusion matrix, showing each icon presented and the number of each icon they were perceived as.

Accuracy. Pearson's correlation coefficient found no relationship between trial number and Accuracy (r (30) = .149, $p>0.05$), suggesting performance was similar throughout the study. The overall identification rate for the two-parameter thermal icons was 64.6% (SD = 47.75). The mean Accuracy for each individual thermal parameter was 96.3% for direction of change and 73.1% for subjective intensity, with 18 missed thermal icons (4.79% of all icons). The confusion matrix for thermal icons is shown in Table 1. Accuracy data was not normally distributed, so non-parametric analyses were used. A Wilcoxon T test found no effect of Mobility on Accuracy, as identification rates were similar when walking (mean = 61%, SD = 49.0) to when sitting (mean = 69%, SD = 46.5). A Friedman's test found no effect of Icon on identification rate either, with mean Accuracy of 74% (SD = 43.8), 61% (SD = 49.1), 57% (SD = 49.7) and 66% (SD = 47.6) for the moderate warm, strong warm, moderate cool and strong cool icons respectively.

Identification Time. Identification time (IDT) correlated positively and significantly with Trial number (*r* (30) = .423, $p<0.05$), with IDT increasing as the number of completed trials increased: identification became more time-consuming over time. IDT data was also not normally distributed, so non-parametric analyses were used. A Wilcoxon *T* test found no effect of Mobility on IDT, with mean times of 9.20s (SD = 3.88s) when sitting and 8.57s (SD = 3.78s) when walking. A Friedman's test found no effect of Icon on IDT, with means of 8.33s (SD = 3.27), 8.83s (SD = 3.77), 9.00s (SD = 3.80) and 9.48s (SD = 4.36) for Moderate Warm, Strong Warm, Moderate Cool and Strong Cool icons respectively. Overall mean IDT across all icons was 8.91s.

5 Discussion

There were some encouraging results from the study, however, some significant issues were encountered which have major implications for the use of thermal feedback for conveying information in mobile, outdoor interaction. Therefore, both positive recommendations and potential obstacles are discussed, which others might draw upon and use to advance the design of thermal feedback.

5.1 Saliency of Direction of Change.

The results show that *direction of change* was extremely well identified, at 96%. Therefore, basic warming and cooling thermal stimulation is highly salient, even when walking outdoors, and both warm and cold stimuli can be felt using simple, compact apparatus. The low-bandwidth feedback designs that simply warm or cool to provide information are therefore likely to be useful even when walking outdoors. Also, thermal *direction of change* may be a suitable replacement for problematic Tacton parameters (roughness or spatial location) for mobile interaction [2].

Recommendations. *Direction of change* is a useful parameter for thermal feedback in mobile environments. If only a single piece of information, with two alternatives, is to be conveyed, then thermal feedback *direction of change* is a suitable means. Based on results here and elsewhere [20], a change of at least 3°C is recommended.

5.2 Walking Does Not Significantly Impair Identification.

Walking outdoors did not significantly affect identification Accuracy (61%), compared to sitting outdoors (69%) in this study. Given the negative effects on perception of thermal changes from walking [20] and environmental temperatures [5] individually, a more pronounced drop in identification when the two influences acted together might be expected. While the Accuracy for sitting and walking outside is quite low, it is encouraging that there appears to be only a small interaction cost when walking.

Recommendations. This result suggests that thermal feedback may be as suitable for use when walking outdoors as when sitting outdoors, however, future research should test identification in a wider range of realistic mobile scenarios, such as on transport.

5.3 Environmental Influences.

Outdoor environmental temperatures significantly impacted identification of thermal icons as, even within the small range of temperatures recorded during the experiment (13-27°C), thermal icons became significantly less identifiable as temperature increased, with long Identification Times of 8-9 seconds. Participants also took longer to identify icons as time went on. No significant correlation was found between trial number and Accuracy, however, so it seems that extra time was taken to maintain Accuracy. Environmental temperature influences skin temperature, which, in turn, influences thermal perception [6, 13, 15]. Warmer environments (and walking) may have elevated the temperature of skin surrounding the Peltiers, potentially leading to domination or referral [3] of warmth and erroneous interpretation of greater warmth at the stimulation site. This could then mask warm changes, as the Δ between skin and stimulus is smaller; and also enhance cooling changes, as Δ is then larger.

Average identification accuracy for both bits of information was 64%, ranging from 87% (during 14.9°C outdoor temperature) down to 33% (at 25-26°C outdoor temperature). The overall value is markedly lower than the 83% accuracy we found for the same thermal icons when sitting indoors [19], although the high value of 87% is slightly higher. The individual differences are worthy of note, however, as one participant managed only 62% at 13.5°C and another managed 83% at 23°C.

Recommendations. From the results, we hypothesize that feedback designs may have to adapt to the environment and adjust the starting temperature and/or the extent/rate of thermal change (see Issues with Subjective Intensity, below) to make the feedback more salient. An example might be to match the starting temperature to current skin temperature. Future research should examine dynamically adjustable feedback.

5.4 Issues with Subjective Intensity.

The main source of error in the study came from the subjective intensity (SI) parameter, as 73.1% were identified correctly (similar to Wettach *et al.* [17]). Analysing the confusion matrix shows that more cold SI were confused than warm SI (60 vs. 41 respectively). This is unexpected, as we are generally more sensitive to cold stimuli [10], however cold stimuli may also feel less intense than warm stimuli [20], which may mean that they were more difficult to tell apart. The Strong Warm icon was closer to the heat pain threshold than the Strong Cold icon was to the cold pain threshold. This may have given the Strong Warm a unique, more intense, quality, making it easier to tell apart from the moderate warmth, a distinction possibly lacking in the two cold icons. Given the performance of subjective intensity, the range of thermal stimuli that can be used to convey information in mobile HCI may be limited. The icon design was based on research that suggests faster and larger changes feel subjectively more intense than slower, smaller changes [11, 15, 20]. The ROCs and temperature Δ values used here may simply not have been fast or large enough to reliably tell apart.

Recommendations. To use subjective intensity as a way of conveying information in mobile HCI, the temperature Δ values should be larger than the 3°C used here, and/or the rates at which the temperature is changed should be more different than 1°C/sec vs. 3°C/sec. Only two Δ values and two ROCs were used in the design of thermal icons. A more thorough examination of the different possibilities could yield stimuli that are more reliably perceivable and perceptually distinct, compared to those used here. Alternatively, our previous work suggested that thermal and vibrotactile feedback can be combined to produce salient "intramodal" icons [19].

5.5 Feedback Alternatives.

If subjective intensity remains an unreliable parameter in icon design, a replacement would need to be sought. Area of stimulation and spatial location are example candidate parameters and research should be conducted to test their suitability. Spatial location may be the more suitable parameter of the two, and has been used successfully in Tactons [2]. Varying the area of stimulation also varies the subjective intensity of the sensation [13], which this research has shown to be a problematic means of conveying information outdoors. However, using a larger stimulator may make feedback more salient [13]: only two $2cm^2$ Peltiers were used in our research.

6 Conclusions

This experiment has been the first to test absolute identification of encoded, two-dimensional thermal icons presented from a mobile phone while participants sat and walked outdoors. In this way, two pieces of information could be conveyed. Identification of both bits of information was lower than expected, at 64.6%, but identification of each individual thermal parameter was promising, particularly direction of thermal change (warming/cooling). Walking outdoors also had no significant impact on identification compared to sitting outdoors. Environmental temperature significantly affected information transmission, however, so our findings have led to several recommendations about how thermal feedback may be better designed to suit mobile interaction, and so improve thermal icon design.

REFERENCES

1. Brewster, S. Overcoming the lack of screen space on mobile computers. *Personal and Ubiquitous Computing*, 2002. 6, pp 188-205.

2. Brown, L., Brewster, S. & Purchase, H. Multidimensional Tactons for Non-Visual Information Presentation in Mobile Devices. *Proc. MobileHCI 2006*, pp 231-238.
3. Green, B. Localization of Thermal Sensation - Illusion and Synthetic Heat. *Perception & Psychophysics*, 1977. 22(4), pp 331-337.
4. Halvey, M., Henderson, M., Brewster, S., Wilson, G. & Hughes, S. Augmenting Media with Thermal Stimulation. *Proc. HAID 2012*, pp 91-100.
5. Halvey, M., Wilson, G., Brewster, S. & Hughes, S. "Baby It's Cold Outside": The Influence of Ambient Temperature and Humidity on Thermal Feedback. *Proc. CHI 2011*, pp 715-724.
6. Hirosawa, I., Dodo, H., Hosokawa, M., Watanabe, S., Nishiyama, K. & Fukuichi, Y. Physiological Variations of Warm and Cool Sense with Shift of Environmental-Temperature. *Int. J. Neuroscience*, 1984. 24(3-4), pp 281-288.
7. Hoggan, E., Crossan, A. & Brewster, S. Audio or tactile feedback: which modality when? *Proc. CHI 2009*, pp 2253-2256.
8. Iwasaki, K., Miyaki, T. & Rekimoto, J. AffectPhone: A Handset Device to Present User's Emotional State with Warmth/Coolness. *Proc. BIOSTEC 2010*.
9. Jones, L.A. & Berris, M. The Psychophysics of Temperature Perception and Thermal-Interface Design. *Proc. HAPTICS 2002*, pp 137-142.
10. Kenshalo, D., Holmes, C. & Wood, P.B. Warm and Cool Thresholds as a Function of Temperature Change. *Perception & Psychophysics*, 1968. 3(2A), pp 81-84.
11. Pertovaara, A. & Kojo, I. Influence of the rate of temperature change on thermal thresholds in man. *Experimental Neurology*, 1985. 87(1), pp 439-445.
12. Salminen, K., Surakka, V., Raisamo, J., Lylykangas, Pystynen, J., Raisamo, R., Makela, K. & Ahmaniemi, T. Emotional Responses to Thermal Stimuli. *Proc. ICMI 2011*, pp 193-196.
13. Stevens, J.C., *Thermal Sensibility*, in *The Psychology of Touch*, M.A. Heller & W. Schiff, Editors. 1991, Lawrence Erlbaum: New Jersey.
14. Stevens, J.C. & Choo, K. Temperature sensitivity of the body surface over the life span. *Somatosensory & Motor Research*, 1998. 15(1), pp 13-28.
15. Strigo, I., Carli, F. & Bushnell, M. Effect of ambient temperature on human pain and temperature perception. *Anesthesiology*, 2000. 92(3), pp 699-707.
16. Suhonen, K., Muller, S., Rantala, J., Vaananen-Vainio-Mattila, K., Rasiamo, R. & Lantz, V. Haptically Augmented Remote Speech Communication: A Study of User Practices and Experiences. *Proc. NordiCHI 2012*, pp 361-369.
17. Wettach, R., Behrens, C., Danielsson, A. & Ness, T. A thermal information display for mobile applications. *Proc. MobileHCI 2007*, pp 182-185.
18. Williams, L. & Bargh, J. Experiencing physical warmth promotes interpersonal warmth. *Science*, 2008. 322, pp 606-607.
19. Wilson, G., Brewster, S., Halvey, M. & Hughes, S. Thermal Icons: Evaluating Structured Thermal Feedback for Mobile Interaction. *Proc. MobileHCI 2012*, pp 309-312.
20. Wilson, G., Halvey, M., Brewster, S. & Hughes, S. Some Like it Hot? Thermal Feedback for Mobile Devices. *Proc. CHI 2011*, pp 2555-2564.