The Heat is On: A Temperature Display for Conveying Affective Feedback

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ABSTRACT
Previous research has investigated whether temperature can augment a range of media including music, images and video. We describe the first experiment to investigate whether temperature can augment emotion conveyed by text messages. A challenge in prior work has been ensuring users can discern different thermal signals. We present an improved technique for thermal feedback that uses an array of three thermal stimulators. We demonstrate that the Thermal Array Display (TAD) increases users' ability to identify temperatures within a narrower range, compared to using a single thermal stimulator. While text messages dominate valence in the absence of context for temperature, the TAD consistently conveys arousal, and can enhance arousal of text messages, especially those that are emotionally neutral. We discuss potential applications of augmenting text with temperature.

Author Keywords
Thermal feedback; thermal haptics; affective computing

ACM Classification Keywords
H.5.2. User Interfaces – Haptic IO.

INTRODUCTION
An emerging trend in CHI research is using temperature to augment. Recent studies have examined temperature conveying qualities, such as emotion, activity level, and social distance [18][40][26].

Human performance in perceiving temperature and its rate of change potentially limits the application of this approach. Cutaneous sense of temperature is carried on nerve endings with slow response times [23] and incorrect perception of temperature results in sensory illusions such as 'synthetic heat' as illustrated by placing a hand on interlaced warm and cool bars [5]. Thermal signals must be sufficiently intense, otherwise they may be difficult for users to perceive correctly, if at all [42]. Along with human factors are limitations of thermal electric coolers (TECs), the technology used in thermal feedback research. Depending on which TECs are used, they can have high power consumption, high latency, and low accuracy.

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We demonstrate latency can be mitigated using an array of TECs. The Thermal Array Display (TAD) is a device worn on the arm that displays patterns of warm, cool, and neutral temperatures using three TEC stimulators. Individually, the TECS are heated and cooled over a small thermal range, but as a group, they signal a wide temperature span. Multiple stimulators also increase stimulated skin area, easing perception of the thermal signal for users.

There are three contributions in this paper. First, we conducted a pilot study to detect if participants could identify warm and cool patterns on their arm. The difficulty of discerning patterns led to investigating if the TAD could instead increase user discrimination of temperature. Results showed participants could identify thermal cues signalled with an array of TECs better compared to the case where only one TEC was used. Second, we conducted another study to demonstrate how thermal cues signalled with the TAD can communicate arousal. Lastly, we proceed to demonstrate that, while text messages dominate valence in the absence of context for temperature, the TAD consistently affects arousal, especially arousal of more emotionally neutral text messages.

BACKGROUND
While vibrotactile feedback (VTF) research is more common to convey information, Suhonen *et al.* reported instances where VTF was misunderstood emotionally [32]. Alternatively, they claimed that temperature could communicate emotional meanings with warmth and coolness, thanks to its bi-directional and continuous advantage over VTF.

HCI literature has investigated whether thermal cues can convey qualities, such as social presence and proximity, [10][26], supporting behaviour such as musical performance, [25] and therapy [35]. AffectPhone [18] mapped arousal to temperature on the recipient's phone, and Lovelet [8] conveyed situation by sensing body temperature and sending it to the other partner. These examples, however, focused on output form novelty and lacked extensive, empirical studies to verify hardware design or the feedback. As noted in the Introduction, human physiology limits effectiveness of thermal communication, and a more detailed examination is needed.

Thermal Feedback System Design

A direction thermal HCI has taken is examining specifics of designing effective sensory output systems. Wilson *et al.* [42] noted 1°C/sec rates of change were appropriate for thermal displays and did not produce stimuli more difficult to detect than 3°C/sec or greater changes. 1°C change magnitudes, on the other hand, were harder to detect than 3°C and 6°C changes and resulted in longer time-to-detections. Users found it harder to detect thermal changes in a mobile setting than when they were seated [42], when wearing stimulators over clothes instead of directly on the skin [15], and when using stimulators outdoors due to ambient temperature interference [13]. Wilson *et al*. combined thermal cues with VTF [39] and examined practical uses of thermal feedback, such as assigning temperatures to activity levels and reviewing restaurants [40]. While results revealed users could detect different levels of temperature, it was not clear, indeed doubtful, if those levels could be discriminated accurately.

Problems of discrimination are primarily due to nonlinear temperature effects that occur when areas of skin in close proximity are exposed to differing temperatures. Due to the low ability of people to discern detailed spatial resolution of the skin's sense of heat, adjacent stimulations affect one other, creating perceptual temperature illusions. These physiological limitations create potential barriers to the effective use of thermal displays.

A key physiological phenomenon in thermal feedback design is *referral*. This occurs when stimulation at one point on the skin is experienced at another location. Green [11] demonstrated this when participants placed their index, middle, and ring fingers on three TECs set to hot and cold patterns. He noted strong sensations outweighed weak ones. Participants found the middle sensation strongest when adjacent stimulators were the same temperature – a form of referral. Referral also occurred when stimulation of the ring and index finger created a sense of temperature applied to the middle finger. When adjacent stimulations mixed hot and cold, users had a (mild) burning sensation termed *synthetic heat*.

Oron-Giland *et al.* [27], created a thermal display comprised of three TEC stimulators worn on the arm. They investigated synthetic heat and primarily looked at spatial configurations of two stimulators turned on in pairs of hot and cold. They found great variance in detection times among participants, and that the thermal detection threshold varied more for hot temperatures than cold. However, their use of multiple TECs only focused on synthetic heat, and they did not examine potential of three-stimulator feedback to communicate thermal patterns to invoke emotion.

Other researchers have used multiple stimulators to explore thermal sensitivity of different body locations. Watanbe *et al.* [36] used two stimulators mounted on a surface that the user's arm rested on. They sent mixed pairs of hot (40°C), cold (20°C), and neutral (33°C) temperatures to participants, who reported the sensations at each stimulator. A major discovery was that extent of referral increases for warm sensations nearer the elbow, or towards the body centre, and cold stimulation has greater referral distance near the hand, or towards the periphery. Participants could judge correctly when both stimulators were set to the same temperature, but had trouble distinguishing if one was set to neutral because of referral. Synthetic heat was also perceived asymmetrically- the wrist does not perceive it, or more generally, thermal referral, as well as if the stimulation occurred nearer the elbow. Thus, stimulator location influences user detection accuracy and perception for hot, cold, or synthetic temperatures.

Multiple stimulators have also been used to address the problem of the time it takes users to discern temperature stimuli. Sato and Maeno [31] found that, although distinguishing thermal stimuli patterns is difficult, multiple stimulators can reduce latency. They created a device consisting of a small 2x2 matrix of TECs that participants placed their fingertips on that exploited the skin's low spatial resolution. Participants could only identify TEC positions at 50% chance levels, but could guess correctly whether the stimulus was hot or cold. Sato and Maeno also demonstrated that patterns of all hot or all cold lowered detection response times compared to mixed patterns. Akiyama *et al.* [1] used two TECs side by side, placed under the hand to 'prime' the skin before sending a hot and cold stimulus. They claimed this reduced detection times up to 28% and 24% for hot and cold, respectively.

Affective Thermal Feedback

Giving someone the cold shoulder or giving them a warm welcome are popular metaphors for communicating abstract concepts that humans harbour toward each other. Concrete experiences, such as sensing temperature, ground such concepts when they are co-experienced, such as affection. This demonstrates a "systemic inter-dependence among language, perception, and social proximity" [17, pp 1214].

Because of this, temperature could be used to alter one's physical state to regulate underlying emotions. Thermoception has both enteroceptive and affective aspects, as both temperature and emotion are processed in the limbic system. Medical studies utilizing PET and fMRI imaging of the brain have shown cooling a patient's right hand linearly correlates with activity in the insular cortex, which regulates internal feelings such as panic, anxiety, sadness, and sexual arousal [6]. Warm stimulation activates distributed regions of the brain associated with affective responses and could induce subjective awareness, such as inner body feelings and emotionality [33].

Social perception involves physical and perceptual content. Lawrence and Bargh described 'Psychological Warmth' to influence a first impression of others. They primed participants by asking them to hold warm and cold beverages before meeting a stranger. Participants primed with warm beverages perceived the stranger more positively than those who held cold beverages [37]. A similar experiment demonstrated that warm beverages induced greater social proximity, and warm, ambient temperatures enabled participants to describe social events more concretely [17]. Subsequently, 'Psychological Cold' influences social exclusion, [43] as excluded participants gave lower estimates of room temperature and craved hotter foods than those not excluded in their study.

As discussed earlier, thermal stimulator prototypes have been used in HCI research to invoke emotional responses, but few have examined the effect of temperature on emotion thoroughly. Salminen *et al.* examined two methods for conveying temperature to invoke emotional responses [30]. In both methods, warming up was sensed as more arousing, dominating, and motivational. Temperature did not affect ratings in pleasantness (valence) and acceptability. Lee and Lim [21] [22] asked participants to investigate information conveyed with wrist worn thermal devices. They found thermal feedback only has meaning in context, but has a unique emotional value which allows for an unobtrusive, casual method of communicating. Heat worked better on a visceral, unconscious level than cognitive, as humans have no legacy for communicating information with heat. Wilson *et al.* [41] examined thermal responses on valence, arousal, and domination. They found useful parameters for temperature to elicit emotional responses but only few emotions were elicited from temperature alone. However, they did not look at thermal augmentation.

Research utilizing thermal augmentation has been used on images and movies, but have only focused on novelty with no significant work relating specific emotions with the stimuli. Hannah *et al.* [16] augmented videos displayed on a television by heating a remote device during happy scenes and cooling it for sad ones. They proposed information could be embedded within the metadata of a movie file for more practical applications. AmbiPad [24] was an Android tablet modified with coloured lighting around the frame and TECs on the back to enhance contents of the screen when it played a movie.

The most intensive research in augmentation was carried out by Halvey *et al.* [12]. They studied the effect of temperature on subjective perceptions of images and music to evoke emotional responses. Images were selected from the International Affective Picture System, and music was selected based on audio dynamics and volume levels. They found temperature could significantly enhance or dampen affective experiences with images. However, no significant differences were found pulsing temperature dynamically with music. They only used three temperatures, and only varied the rate of change as a parameter.

No similar research has augmented text with temperature. Though Thermal Hug Belt [10] examined how temperature could mediate a sense of social presence when subjects used IM chat, they did not examine how temperature could elevate or decrease emotion, as text was not controlled.

To summarize the literature review, research has shown that temperature can effectively communicate meanings, such as emotional state. [32][18][8] demonstrated temperature eliciting such reactions from participants. Furthermore, studies have examined key parameters for designing thermal feedback, such as Wilson *et al.*'s work, [42][15][13][39][40]. Green [11], Oran-Giland *et al.* [27], Watanabe *et al.* [36], Sato and Maeno [31], and Akiyama *et al.* [1] incorporated multiple stimulators into their work to investigate perceptual aspects of temperature. However, they focused on physiological aspects and were not necessary HCI related. Thus, gaps in the knowledge remain:

- Can multi-stimulator thermal devices relay more complex patterns akin to vibrotactile patterns [3]?
- Can users' thermal sensory acuity be boosted further than previous work [31][1]?
- Can temperature augment emotion when paired with social media messages?

HARDWARE OVERVIEW

We constructed the Thermal Array Display, or TAD, to investigate these knowledge gaps. First, we examined how accurately users could distinguish thermal patterns. The TAD device, shown in Figure 1, is worn on the arm and can signal thermal patterns using three stimulators.

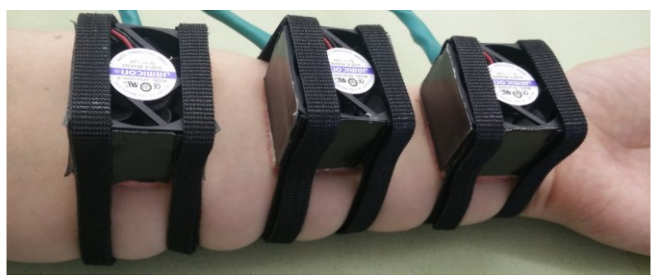


Figure 1. The Thermal Array Display

Most modern thermal output systems use TECs: flat, rectangular, thermoelectric components that cool down and heat up on either side depending on how current is applied. By varying voltage using Pulse Width Modulated (PWM) signals from a micro-controller, one can control how much heat is transferred from the cool side to the warm side, depending on rise time of the signal. When polarity is reversed to a TEC, the heat transfer direction reverses, allowing either side to warm up or cool down. This behaviour can be moderated using an H-Bridge circuit, which is implemented in motor drivers. By using a Proportional-Integral-Derivative (PID) controller, one can set the temperature of the TEC by reading current temperature using a thermistor and appropriately updating output and direction of the current to the TEC.

In our system, an Arduino Mega 2560 is used to control three TECs independently. Each TEC (MCPE1-01708NC-S, Multicomp) is connected to a thermistor (MC65F103A, Amphenol Sensors) that is polled in the Arduino main loop. As Arduino pins are rated at only 40 mA, the TECs are driven by a motor driver (MC33926, Pololu), which draws power from a 6V, 10A mains supply. Each TEC is connected in series with an inductor to 'smooth' the PWM signal from the motor driver to appear as a DC current source. This signal is pulsed at 490 Hz, as it produced the most stable temperature behaviour compared with other frequencies attainable on the Arduino.

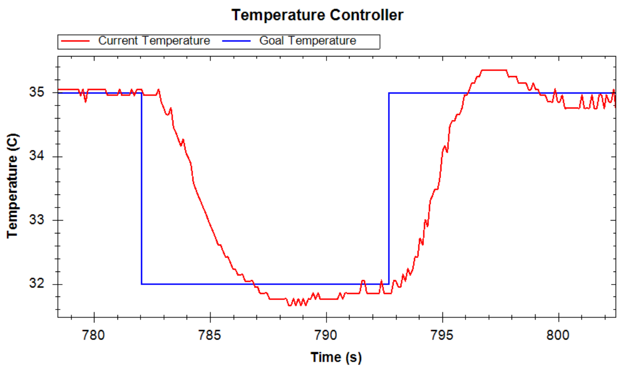


Figure 2: Temperature Plot

Maintaining a fixed rate of change is difficult using a PID controller. After careful tuning, we achieved, on average, 1°C/s rates of change using tuning parameters of K_p=50, K_i=2, and K_d=0, the proportional, integral, and derivative constants, respectively. Figure 2 shows a time plot of temperature changes using the system, first cooling from 35°C to 32°C and then warming up back to 35°C.

Figure 3 shows the stimulator pad construction. Design is based Oron-Giland *et al.*'s device [27], the only instance of an arm-worn, three-stimulator display in literature. Each stimulator consists of a TEC, attached to a heat sink (BGA-STD-115, ABL) using double-sided thermal tape. A 5V DC fan is attached on top of the heat sink by gorilla tape. Fans are driven from an external power supply using BD137 NPN transistors. Both heat sinks and the fans are needed to extract heat away from the TECs. Otherwise, the efficiency of the TECs decreases as they heat up, potentially posing a safety hazard. The participant was insulated from the heat sink using a panel of cardboard and Styrofoam glued together. Double-sided Velcro was glued to both sides of the heat sink, which allows users to wear the stimulators by strapping them around the arm.

Oron-Giland *et al.* used a thin, 3mm thick, metal plate at the point of contact between the skin and the TEC itself. This involved drilling a hole in one of the plate's four lateral surfaces to insert the temperature probe into. This is an alternative to mounting the sensor directly on top of the TEC, as is done in most systems reported and allows the stimulator to be comfortably worn. It also protects the sensor from exposure to the ambient environment, which may result in less reliable readings. Instead of using aluminium for the plate however, we used C101 copper due to its superior heat transfer properties. Before inserting the probe, the hole was filled with thermal grease (MX-4, Artic). After insertion, it was sealed with epoxy.

Figure 3: A Single Stimulator- Bottom (Left) and Top (Right)

Software consists of Arduino firmware and a PC user interface. The Arduino monitors temperature from the thermistors, connected as part of a voltage dividing circuit that feeds into the Arduino's analog pins. This raw voltage input is converted into degrees Celsius using the Steinhart-Hart thermistor equation. The PC software interfaces with the Arduino using the USB serial library CMDmessenger [7]. The basic functionality sets the temperature of each TEC separately, monitors safety, reads parameters from files, and logs participant data in real-time.

PILOT STUDY

The initial aim of the TAD was developing a pattern-based, thermal-tactile language. We conducted a short pilot to see if users could identify patterns of three stimulators set to warm, cool, or neutral temperatures.

- Participants wore the TAD and were shown visual representations of eight thermal patterns.
- Participants were instructed to select one they believed was 'displayed' to them.
- Each pattern was used twice.

Oron-Giland *et al.* [27] proposed patterns of three alternating thermal stimuli but no study was conducted. Wilson discussed the ideas of area stimulation and 'thermal waves' [38], like unidirectional vibro-tactile rhythms [3]. However, he did not pursue it due to perceptual problems and technological issues. This research carried out a pilot study to investigate this further.

As the TAD uses three stimulators, 27 patterns are achievable with warm, cool, and neutral temperatures. A taxonomy was devised to categorize such patterns. Each had a 'mechanical' device setting and a 'perceived' effect derived from physiological illusions [11] and the anticipated spatial direction the temperature would travel [36]. Two parameters were used: the temperature direction (hot, cold, and neutral) and TEC arm positioning, (elbow, middle of the forearm, and wrist). Table 1 illustrates a few of these.

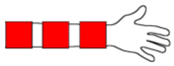
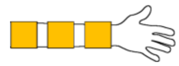
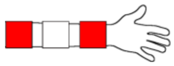
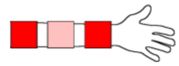
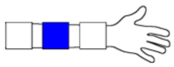
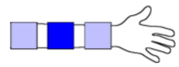
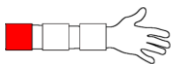
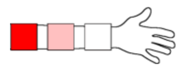
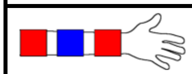
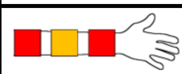
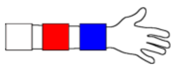
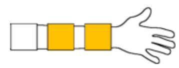
Mechanical	Description	Perceived
	Enhanced Hot	
	Inward Referred Hot	
	Outward Referred Cold	
	Proximal Referred Hot	
	Synthetic Heat	
	Distal Optimal Synthetic Heat	

Table 1: Thermal Patterns

Pilot studies revealed similar findings to Sato and Maeno [31]: participants could not easily identify temperature of the individual TECs when presented simultaneously. We therefore investigated whether the TAD could improve ability of users to accurately identify single temperature states. The TAD increases the skin area that is stimulated which could potentially enhance signal intensity, making perception of temperature easier to discriminate.

Two further studies were conducted with the TAD. The first compared two methods of signalling temperature with three stimulators and compared accuracy of users' responses to the case where only one stimulator was used. Participants recorded responses on a 7-point Likert scale (Figure 4), where each point, illustrated as a radio button, corresponded to a temperature state of the TAD (Table 2). The second study investigated if thermal cues could convey emotion by measuring valence and arousal when participants viewed positive, neutral, and negatively rated Facebook messages on-screen with temperature.

EXPERIMENT 1

Participants were asked to identify seven thermal stimuli using three methods: Single, where only one stimulator was used, Amplification, where all stimulators were set to the same temperature, and Quantification, where the target temperature was represented by setting one, two, or all three stimulators to the warmest or coolest temperature.

- The Single, Amplification, and Quantification tests were presented in random order.
- Each test had a calibration session beforehand to acquaint participants with stimuli.
- During each test, seven temperature stimuli were presented three times each, and the skin temperature returned to neutral before each was presented.
- Participants made selections on a 7-point Likert scale.
- There was a five-minute break in between each test.

Stimuli Design

Three parameters were considered when designing the temperature stimuli: neutral temperature; temperature range; and the temperature difference between stimuli. We discuss each in this section and then describe how we signalled temperature using the TAD.

Since skin adapts to stimulation, consideration was made which temperature to use as the neutral stimulus or baseline temperature. This neutral temperature varies from person to person, but it is thought to be in the range of 20°C - 40°C [19]. Within this range, skin will adapt slowly to reduce the sensation of stimulation until full re-adaptation has taken place and the user no longer perceives any sensation. Temperatures closer to the middle of this range are easier to adapt than at the extremes [14]. Beyond this range, temperatures feel persistently cold or hot [20]. Such extreme temperatures are not commonly used as they are uncomfortable and painful. We chose a conservative temperature of 32°C as was used in Wilson and Halvey *et al.*'s work [39][42][13][25].

The use of wide temperature ranges requires more time to reach the extreme temperatures. This results in longer latencies, the time between temperature changes. It is paramount to use as small a range that can be detected to reduce time taken for the TECs to change temperature, and thereby reduce the time to communicate a temperature state. Limiting the number of thermal scale points and the temperature difference between them minimizes the total temperature range needed for a feedback system.

Wilson *et al.* used a temperature range of 22°C-38°C with 2°C as the smallest difference between two stimuli [40]. Within this range is a safe and comfortable zone of temperatures appropriate for thermal feedback. In contrast, we chose a narrower range of 29°C - 35°C and reduced the step between stimuli to 1°C. These two changes reduced the time to signal different temperature states. More importantly, smaller step changes make it more difficult to discern neighbouring states. This forms a better apparatus for testing fine stimuli discriminability with multiple TECs.

Table 2 shows how temperature was signalled in each test. Squares represent stimulators, where the left, middle, and right squares represent the wrist, middle, and elbow stimulators, respectively. Colours denote whether the stimulus was warm, cool, or neutral using red, blue, and white, respectively. Colour saturation indicates stimuli intensity. There are three intensities for warm and cool.

Single Test

This test used only the middle stimulator. The middle stimulator was chosen to prevent biasing effects from using either the elbow location, which would have made warm sensations stronger [36], or the wrist, which is the direction cold sensations spread better towards. Other stimulators were not worn as it eliminated the decision of whether to leave them on (at neutral) or off. Participants were asked to identify which of the seven stimuli was presented. Stimuli differed by 1°C increments with neutral at 32°C. Hence, warm was 33°C, warmer was 34°C, and warmest was 35°C. Cool was 31°C, cooler was 30°C, and coolest was 29°C.

Amplification Test
This method represents intensity by setting all stimulators to the same temperature. All three stimulators were worn, and the participants were asked to identify the combined stimulus. As with the single test, temperature states differed by 1°C increments with neutral at 32°C, applied to all three stimulators, using the temperatures from the Single test.

Quantification Test
Participants were asked to discriminate cues wearing all stimulators, however, this approach used only 29°C for cool stimuli and 35°C for warm stimuli. It is the number of active stimulators that determines the intensity rather than indicating intensity by temperature. Thus, warm set one stimulator to 35°C, warmer set two stimulators to 35°C, and warmest set all stimulators to 35°C. Cool set one stimulator to 29°C, cooler set two stimulators at 29°C, and coolest set all three stimulators to 29°C. Stimulators that are not set to either 29°C or 35°C were left at 32°C, neutral.

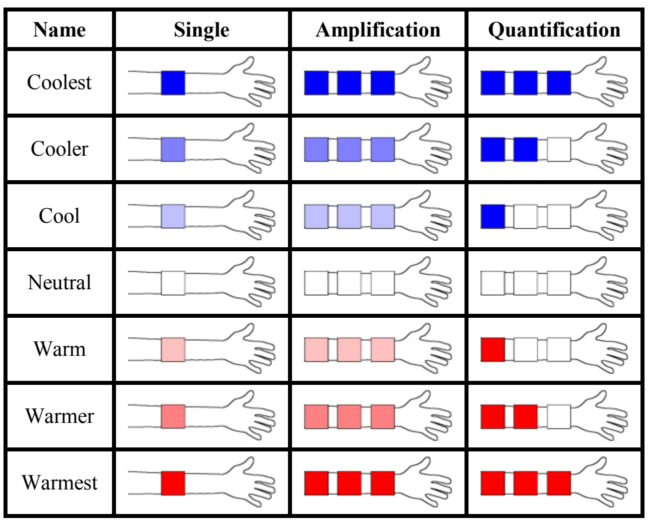


Table 2: Experiment 1 Stimuli

Procedure
Twelve participants, ten males and two females, were recruited from the engineering school of a UK university. While gender differences are a debatable subject in thermal perception studies, the most recent paper by Wilson *et al.* [41] showed no differences in perceiving temperature. Each participant received £10 for their time, in line with standard practices at the institution, and the experiment was approved by the school ethics board in advance.

To ensure both wellbeing of participants and efficacy of the study, exclusions were made. Individuals could not participate if they had medical problems that could impede temperature perception, such as over-sensitive skin, or where exposure to temperature causes discomfort or harm.

Participants wore the TAD on their non-dominant arm, following the practice of previous studies [40]. Each participant took approximately one hour to complete the experiment, including induction and completion of all tests. There was no time limit imposed on participants, thus the duration lasted until they submitted their selections for each trial. Participants, however, were instructed not to dwell on answers and to move on as quickly as they could.

The entire experiment was automated. Tests were separated by five-minute breaks to allow participants to relax their arms. Participants were told to read the instructions on screen and complete the tests by recording their perception of the signalled temperature on a 7-point Likert scale, shown in Figure 4. Each point denotes one of the states, colour coded from 'Coolest' to 'Warmest', with 'Neutral' in the middle. The seven stimuli were presented three times, in random order for each test. The order of the three tests was also randomized by counterbalancing beforehand.

Preceding each test was a calibration session to familiarize participants with the stimuli presented and the user interface. This session was nearly identical to the real tests that followed, but the Likert scale was pre-selected with the correct response. Additional color-coded graphics depicted the position of stimulators on the arm, with instructions on navigating the interface, and the displayed name of the selected stimulus, e.g. 'Warmest' or 'Neutral'.

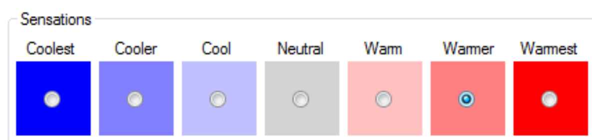


Figure 4: User Interface

Between each stimulus was a short delay to allow the skin temperature to re-adapt back to neutral. This process, discussed in the Stimuli Design section, ensured participants could discern the next trial without bias from the proceeding stimulus. It also serves to establish the reference temperature for judging subsequent stimuli. Previous studies used delays between ten seconds [40] to two minutes [15] for re-adaptation. We chose the shortest time of ten seconds due to time constraints of the study. Our temperature range was even smaller than the range used in [40], so this time was deemed acceptable. After re-adapting, the next stimulus was presented for three seconds and then the scale was displayed on screen for selection.

Results
We first tested the error rate (frequency) for all three presentations, using a chi-squared test. This produced $\chi^2 = 10.89$, df=2, p=0.004. The Single method provided the worst outcome, with 34.9% correct judgments, while Amplification and Quantification produced 49.2% and 44.4% correct ratings, respectively.

We also tested the degree of error, the absolute difference between the target and actual values. The degree of error was measured separately from error rate as non-significance in either test would lead to rejecting the alternate hypothesis. A Kruskall-Wallis test on the degree of error produced H=22.59, df=2, $p < 0.001$. Again, the multi-stimulator approaches both proved superior to the single stimulator. The alternative test for the population distribution of errors using chi-squared also proved significant (from errors of 1 to 5, calculated from the error formula above) and produced χ^2=20.55, df=8, p=0.001. The multi-stimulator methods gave more accurate detections, and resulted in lower degrees of error. As the data was not normally distributed, ANOVA was not used.

Subsequent testing for the precision of the two methods produced a clear advantage for the amplification method in terms of exact ratings (χ^2= 4.51, df=1, p=0.036), but there was no difference in the relative degree of error. This suggests that Amplification is the most promising method for signalling thermal states, but as the advantage over Quantification was low-power, both multi-stimulator approaches are more accurate alternatives to the traditional single stimulator method and merit further study.

EXPERIMENT 2

We examined how temperature could be used as an augmenting modality for Facebook post messages. The experiment consisted of two studies: a pilot study that selected appropriate media from an existing corpus of Facebook messages and thermal stimuli; and a main study which combined the messages and thermal stimuli in pairs to investigate whether temperature could augment the emotion communicated by the Facebook posts.

For both studies, twelve participants were selected from the engineering school of a UK university. Like the previous experiment, each participant received £10 for his or her time, and the same exclusions rules were applied. Nine males and three females were used in the pilot, which took about 40 minutes to complete. For the main study, which took about an hour to complete, twelve new participants comprised of four males and eight females were used.

Pilot Study

A two-part pilot was conducted to verify messages and thermal stimuli appropriate for the main study. First, participants evaluated valance and arousal of messages from a previous study [28]. Next, participants rated valance and arousal of the thermal stimuli from Experiment 1.

- In Part 1, participants rated twenty-five messages, each repeated three times.
- In Part 2, participants rated seven temperatures using Amplification, repeated three times each.
- Participants were given written instructions for both parts and a five-minute break in between.
- Participants reported valance and arousal selections on two 5-point SAM scales.

Stimuli Selection

Augmentation of text messages using temperature could be studied by examining impact of valence and arousal. Research investigating text messages and emotion such as [9] have demonstrated agreement between expert trained users and naïve (non-emotion expert) users when rating emotions from the Russell circumplex model [29]. Though databases of such messages exist [34], early pilots revealed difficulty of obtaining suitable messages that our non-expert participants agreed were happy or unhappy and excited or calm. Instead, we utilized results of a recent study [28] that rated Facebook posts by psychological trained annotators based on valence and arousal traits.

Similar to Halvey *et al.* [12] we selected messages for each emotional state: high valance/high arousal, high valence/low arousal, low valence/high arousal, low valence/low arousal, and neutral valence/neutral arousal. As the study in [28] rated messages on 9-point scales, any message rated 1-3 by both experts in the study was selected as a candidate for either low arousal or low valance. Messages rated 7-9 were candidates for high arousal or high valance. Messages that were rated 5 for both valance and arousal were candidates for the neutral stimulus. We used these criteria as there were only few instances of messages that had either 1 or 9 ratings for valence and arousal that were consistent across the reviewers. Neutral messages with ratings of 5 were abundant, and we did not have to extend their score range to 4-6 for inclusion. Along with the text messages, the thermal stimuli described in the Amplification section were also evaluated emotionally.

A 5-point Self-Assessment Manikin (SAM) technique [2] was employed to capture participants' valence and arousal reactions to both the temperature and message stimuli. In light of the experience of participants in the first study we aimed to simplify the effort required to rate signals. For this reason, we did not use the 9-point SAM scale used in the Facebook study, nor did we use the 7-point scale from Experiment 1 as we were not measuring discrimination of the seven thermal stimuli.

Procedure

To ensure consistency across participants, stimulator positions were marked on the arms before the study. Elbow distance to the wrist was measured; the midpoint was marked for placement of the middle stimulator to compensate for differing forearm lengths. Furthermore, participants were given a brief 'calibration' session where they were presented the warmest and coolest stimuli to ensure they could detect these temperatures and to allow themselves to become familiarized with the TAD.

After the setup, participants completed the two parts of the study. In Part 1, they rated the Facebook messages. They were instructed to read the message that appeared at the top of the screen and were given the context to imagine it was sent from a close friend on Facebook. Participants rated valence and arousal using the SAM as shown in Figure 5.

After completion, the TAD device was then attached to their non-dominant arm and they proceeded to rate the thermal stimuli. Unlike the messages, the temperatures were not given a context in the instructions, and participants were instructed to just rate how the temperatures made them feel while perceiving them. Like Experiment 1, ten seconds was used to re-adapt the skin to return to a baseline temperature in between trials. All stimuli for both parts were repeated three times in a random, counter-balanced order unknown to either the participant or the lab monitor until after the test. Like before, there was no time limit to making selections.

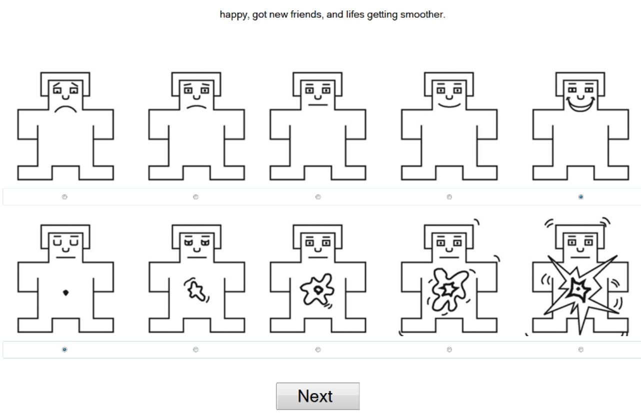


Figure 5: SAM Interface. The small text at the top is the Facebook message post.

Results – rating message valence and arousal

Participants could differentiate messages per valance and arousal. Table 3 shows the five messages selected for the main study, with mean valance and arousal scores. As a 5-point scale was used, neutral scores are 3. Message 1 was selected as the high valence/high arousal text, Message 2 as high valence/low arousal, Message 3 as low valence/low arousal, Message 4 as low valence/high arousal, and Message 5 as the neutral message.

ID	Message	V	A
1	Blessed with a baby boy today	3.6	3.5
2	life is beautiful	3.7	2.3
3	SICK AGAIN !!!! HATE IT !!!!!	2.3	2.4
4	At least 15 dead as israeli forces attack Gaza aid ahips!!!!!!! i hhhhhhate israil	1.4	3.8
5	And one careless match can start a forest fire but it takes a whole damn box to get a campfire going!	3.1	2.8

Table 3: Selected Messages

Figure 6 shows the valence and arousal means from Table 3 in a scatterplot, with the horizontal axis denoting the valence scale and the vertical axis denoting the arousal scale. Quadrants above the horizontal axis denote messages with high arousal and the bottom two quadrants denote messages with low arousal. Messages to the right of the vertical axis are high valence (happy), and messages to the left of the vertical axis are low valence (unhappy). The selected messages fall within their respective quadrants showing appropriateness for their valence and arousal traits.

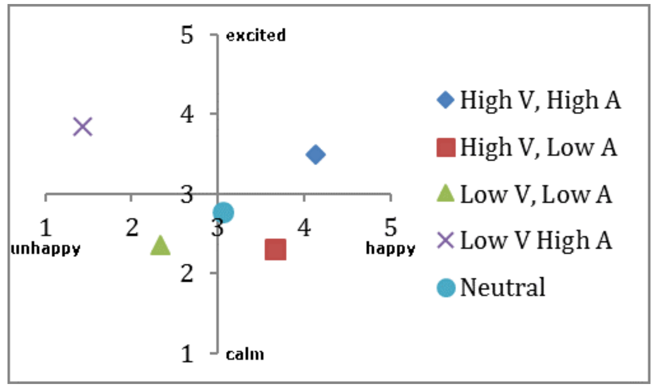


Figure 6: Selected message mean valence and arousal scores

Results – rating temperature valence and arousal

Participants disagreed which temperatures had a high or low valence. Six participants interpreted cool stimuli as high valence and warm as low valence. Two did the opposite: rating warm stimuli as high valence and cool stimuli as low valence. The remainder rated either all stimuli as low valence or only certain scales of warmth or cool as high valence. This was surprising, as [21] reported participants rating warm as high valence and cold as low valence. However, they only assessed this using qualitative data. Salminen *et al.* [30] on the other hand, concluded temperature did not affect pleasantness (valence) ratings and that it only affected arousal and dominance. Some research has been mixed. Halvey *et al.* [12, pp. 95] reported warm stimuli were given higher valence ratings than cool stimuli "with some exceptions", though they did not explain why neutral temperatures had higher valence ratings than warm stimuli.

On the other hand, there was general agreement amongst participants perceiving more intense stimuli as more arousing. Participants found scales of warm to be more arousing than cool scales. This may have depended on how intense they perceived the stimuli as some participants remarked warm stimuli felt more intense than the cool ones. Our findings here agree with prior literature.

The mean time to rate the messages was 6.82 sec (sd = 1.5 sec). The mean time to rate thermal cues was 6.84 sec (sd = 0.8 sec). This suggests that, despite latency of thermal cues, they require no more cognition than reading text messages.

Main Study

We proceeded to examine interaction between text messages and thermal stimuli. As discussed, research has examined emotions and thermal stimuli separately, as well as using temperature to augment images and music. However, it has yet looked at whether thermal cues can augment emotions communicated in text messages.

- The study consisted of 96 trials that were comprised of 48 unique stimuli that were each used twice.
- 12 trials were message-only stimuli. 72 were pairs of a message and temperature, 12 were temperature alone.

- The 12 message trials were tested together either before or after the other 84 trials.
- The 84 thermal trials were split into 3 blocks with 5 minute breaks between them.
- For all 96 trials, the participants reported valence and arousal on two 9-point SAM scales.

SAM scales were increased to nine points from five points. This was done as almost every participant in the pilot rated temperature using only the 2-, 3-, or 4-point selections and some participants remarked they would have preferred a wider range of choices. It should be emphasised that the stimuli chosen from the pilot were re-tested again in the manner they were presented alone in the pilot- results of the 5-point and 9-point scales were not 'mixed'.

The seven thermal stimuli were combined into pairs with one of the five message types or a blank message (for the temperature only condition) and displayed to the participant. Each pair was presented to the participant twice during the test, resulting in 84 trials. As before, there was a ten second re-adaption period between each trial. The order of all trials was randomized and divided into three blocks, with five-minute breaks between blocks to prevent fatigue.

Conditions where either the messages were displayed without temperature or thermal cues were displayed alone were tested again, due to the switch from 5-point SAM scales in the pilot to 9 points used in the main study. As it would have been difficult to detach the thermal device each time the message only stimulus was presented, they were tested separately from the rest of the thermal stimuli trials. To prevent ordering effects resulting from this, participants were split into two groups. The first group rated the messages and then proceeded to rate the other 84 thermal trials, and the second group rated the 84 thermal trials and then proceeded to rate the messages.

Results

We first tested the distribution of the participants' ratings of valence and arousal. Researchers have previously raised concerns on the validity of using ANOVA on Likert data, but when data is normally distributed, ANOVA is appropriate [4, p. 126] and can test for interaction effects.

To test for normality of the data, we used Shapiro-Wilkes tests for the data set as a whole, and then separated the data by message and thermal stimuli to ensure that all subsets were also normally distributed. All results produced $W>0.975$, and exceeded the critical values at $p<0.01$. This confirmed the normality of the data, and permitted the use of ANOVA.

The ratings for valence had a global mean of 4.8 and a standard deviation of 1.9; while arousal had a mean of 4.7 and standard deviation of 1.6. To again test for the validity of ANOVA on the data, we obtained standard deviations for the subsets of thermal and message stimuli, with valence ranging between 1.1 and 1.7, and arousal from 1.8 to 2.1. The level of variance in standard deviations was within the tolerances expected of a two-factor ANOVA.

Two tests allowed us to check for experimental effects from wearing the apparatus. First, we tested the temperature-only stimuli results against the trials that paired thermal signals with a neutral message. Second, the message-only responses were tested versus the same messages with a neutral thermal signal. Any positive result would indicate an undesirable substantial experimental effect. Using ANOVA, F values varied between 0.07 ($p>0.85$) and 1.5 ($p>0.20$). For the main effects, scores were at or above $F=8.5$ ($p<0.005$) Thus, we could discount the likelihood of a significant side effect from wearing the device.

The global descriptive data suggests that arousal responses were diffuse and inconsistent, whereas valence responses were more concentrated and consistent. As such, valence will be addressed first before proceeding to testing arousal.

We first tested valence using the message and thermal stimuli as the two variables. The ANOVA result was $F(2,385) = 118.45$ ($p < 0.001$) for the messages dimension, but the thermal dimension yielded $F = 0.43$, and interaction produced $F=0.29$, both very far from significant. While messages substantially influenced the perceived valence, thermal signals had no discernible effect.

For arousal, the ANOVA result was $F(2,385)=3.62$ ($p<0.05$) for message effect and 3.41 ($p<0.05$) for thermal effect, with the interaction producing $F=0.20$ ($p>0.80$). There is again no evidence of an interaction effect. Both the message and the thermal stimulus had a similar and reliable effect, but neither was as marked as the impact of the message on valence.

Thus, for valence and arousal, the message content had a reliable main effect. The effect was much more powerful in valence than arousal. In contrast, thermal stimulation had no reliable effect on the valence, but had a similar level of efficacy to the message for arousal levels.

Discussion

Figure 7 shows the plots of the mean valence and arousal scale responses (y-axis) as a function of temperature change (x-axis) for each category of message and thermal pairings. Plot (a) shows the pairing with a blank message for testing temperature only. The bottom of the y-axis denotes ratings of 1 on the valence and arousal scales (unhappy and calm), and the top of the y-axis denotes ratings of 9 on the scales (happy and excited). The far right of the x-axis denotes the coolest temperature setting and the far left denotes the warmest setting, with neutral at the position of the y-axis.

Arousal is marked by the red lines in each plot. As expected, as temperature increases, arousal ratings generally tend to move upward. Except for plot (c), arousal ratings tend to be negative for cooler temperatures and only cross the x-axis when warmer stimuli are applied. For all categories, temperature had a reliable main effect on arousal, including plot (f).

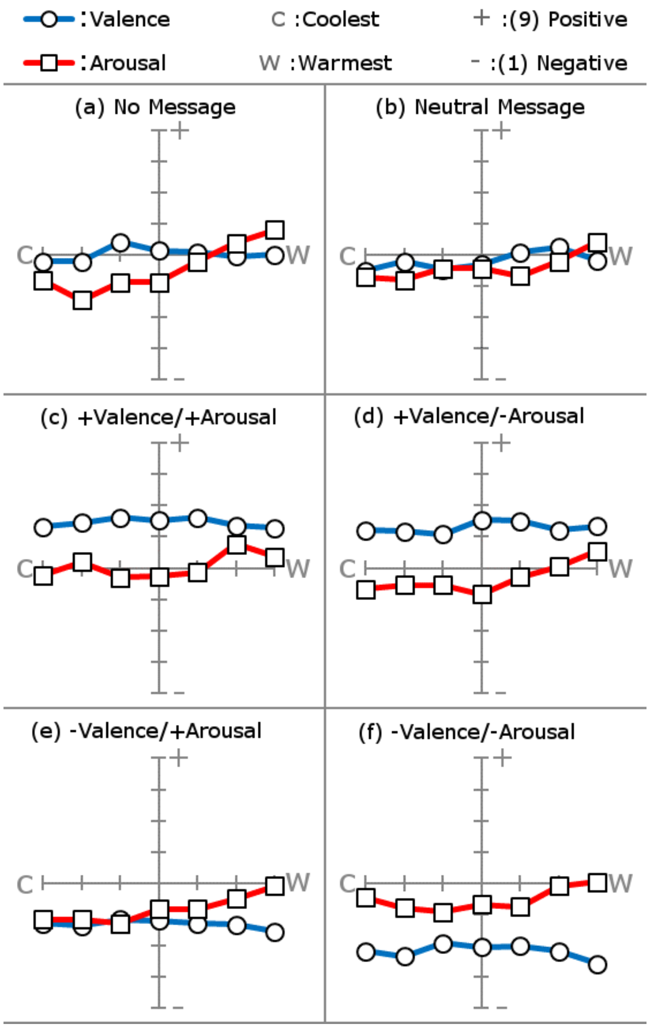


Figure 7: Message and temperature pairing mean plots for valence and arousal

Valance is marked with the blue line. As discussed in the Results section, temperature had no reliable effect. As plots (c), (d), (e), and (f) illustrate, the valance of the message clearly dominated, with the lines clearly above or below the x-axis. These lines remained relatively straight, regardless of thermal stimulus applied. For plot (a), where only temperature was displayed with no message and plot (b), where temperatures were paired with the neutral message, the means remained close to neutral. Plot (a) illustrates pilot test findings with no thermal valence effect.

Why did we not observe a thermal effect on valence? Lee and Lim offer some clues. They reported environmental factors could influence thermal expression, as humans tend to feel safe from factors that change body temperature [21]. We did not control this, and though thermal feedback recommendations still hold in varying ambient temperatures [13], it may influence thermal expression of valence. [21, p. 4235] also reports "heat seems to have hardly any meaning by alone without its context". As we instructed participants to "rate how the temperature made you feel" this context may have been ambiguous, as we did not ask them to interpret it in a context like with the messages. Future research should address the effect of context on the affective perception of thermal cues in different environments, including a control condition where temperature is sent ambiguously.

We can conclude that temperature itself consistently generates arousal responses. In a temperature-augmented message, strong textual valence will dominate the emotion communicated to the user. For all messages, but particularly if the message is neutral, temperature significantly influences the emotional arousal communicated.

CONCLUSION

Users find it hard to identify the physical position of TECs when they are placed in patterns. However, the TAD enabled more accurate discrimination with smaller temperature differences between thermal signals, reducing time for user identification of thermal state changes. In our test of single- versus multi-TEC methods, the single-TEC method had the worst error rate and degree of error. We deployed two multi-TEC methods: Amplification set all TECs to the same temperature, with the temperature indicating the system state; Quantification used the number of TECs set to hot or cold to indicate the state. The error rate and degree of error for Amplification were significantly lower than the Single method. Quantification was superior to the Single method but had higher error rates than Amplification. However, there was no significant difference in degree of error between the two multi-TEC methods.

Temperature without a message context gave arousal reactions but did not provide valence. Warm temperatures were perceived as more arousing than cool temperatures. For valence, message content was highly effective, and heat was ineffective. Temperature exerted a discernable and reliable effect on arousal when paired with neutral messages. This effect was also seen when paired with low and high arousal messages, providing a similar influence on arousal to text. No reliable interaction effect was found between temperature and message for arousal.

Thermal signals portrayed emotional arousal to participants as effectively as text. We suggest two areas where this feedback may be useful. Those with cognitive impairments, such as Autism, which impede their sense of emotional message content, could potentially benefit. Thermal cues could allow them to sense that a message is, for example, intended to excite them. Another possible application is education, where language learning could be reinforced by augmenting foreign sentences with temperature, which are mapped to intended emotional meanings of words.

REFERENCES

1. Shimon Akiyama, Katsunari Sato, Yasutoshi Makino, and Takashi Maeno. 2012. Presentation of thermal sensation through preliminary adjustment of adapting skin temperature. In *Haptics Symposium* (HAPTICS '12), 355-358.
2. Margaret M. Bradley and Peter J. Lang. 1994. Measuring emotion: the self-assessment manikin and the semantic differential. *Journal of behavior therapy and experimental psychiatry* 25, 1: 49-59.
3. Lorna M. Brown, Stephen A. Brewster, and Helen C. Purchase. 2006. Multidimensional tactons for non-visual information presentation in mobile devices. In Proceedings of the 8th conference on Human-computer interaction with mobile devices and services (MobileHCI '06). ACM, New York, NY, USA, 231-238.
4. Paul Cairns and Anna L. Cox. 2008. Research Methods for Human-Computer Interaction (1st ed.). Cambridge University Press, New York, NY, USA.
5. Arthur. D. Craig and M.C. Bushnell. 1994. The thermal grill illusion: unmasking the burn of cold pain. *Science* 256, 5169: 252-255.
6. Arthur D. Craig, Chen Kewei, D. Bandy, and Eric M. Reiman. 2000. Thermosensory activation of insular cortex. *Nature neuroscience* 3, 2: 184-190.
7. CMDMessenger Library. Retrieved March 22, 2016 from http://playground.arduino.cc/Code/CmdMessenger
8. Hidenori Fujita and Kazushi Nishimoto. 2004. Lovelet: a heartwarming communication tool for intimate people by constantly conveying situation data. In *CHI '04 Extended Abstracts on Human Factors in Computing Systems* (CHI EA '04), 1553-1553.
9. Alastair J. Gill, Darren Gergle, Robert M. French, and Jon Oberlander. 2008. Emotion rating from short blog texts. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '08), 1121-1124.
10. Daniel Gooch, and Leon Watts. 2010. Communicating social presence through thermal hugs.
11. Barry G. Green. 1977. Localization of thermal sensation: An illusion and synthetic heat. *Perception & Psychophysics* 22, 4: 331-337.
12. Martin Halvey, Michael Henderson, Stephen A. Brewster, Graham Wilson, and Stephen A. Hughes. 2012. Augmenting media with thermal stimulation. In *International Conference on Haptic and Audio Interaction Design*, 91-100.
13. Martin Halvey, Graham Wilson, Stephen Brewster, and Stephen Hughes. 2012. Baby it's cold outside: the influence of ambient temperature and humidity on thermal feedback. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12), 715-724.
14. Martin Halvey, Graham Wilson, Stephen A. Brewster, and Stephen A. Hughes. 2013. Perception of thermal stimuli for continuous interaction. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems* (CHI EA '13), 1587-1592.
15. Martin Halvey, Graham Wilson, Yolanda Vazquez-Alvarez, Stephen A. Brewster, and Stephen A. Hughes. 2011. The effect of clothing on thermal feedback perception. In *Proceedings of the 13th international conference on multimodal interfaces* (ICMI '11), 217-220.
16. David Hannah, Martin Halvey, Graham Wilson, and Stephen A. Brewster. 2011. Using multimodal interactions for 3D television and multimedia browsing. In *Proceedings of the 9th international interactive conference on Interactive television* (EuroITV '11), 181-184.
17. Hans IJzerman, and Gün R. Semin. 2009. "The thermometer of social relations mapping social proximity on temperature." *Psychological science* 20, 10: 1214-1220.
18. Ken Iwasaki, Takashi Miyaki, and Jun Rekimoto. 2010. AffectPhone: a handset device to present user's emotional state with warmth/coolness. In *Proceedings of the 1st International Workshop on Bio-inspired Human-Machine Interfaces and Healthcare Applications*, 83-88.
19. Lynette A. Jones, and Michal Berris. 2002. The psychophysics of temperature perception and thermal-interface design. In *Proceedings of the 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (HAPTICS '02), 137-142.
20. Dan R. Kenshalo and Harley A. Scott. 1966. Temporal course of thermal adaptation. *Science* 151, 3714: 1095-1096.
21. Wonjun Lee and Youn-kyung Lim. 2010. Thermo-message: exploring the potential of heat as a modality of peripheral expression. In *CHI '10 Extended Abstracts on Human Factors in Computing Systems* (CHI EA '10) 4231-4236.
22. Wonjun Lee and Youn-kyung Lim. 2012. Explorative research on the heat as an expression medium: focused on interpersonal communication. *Personal and Ubiquitous Computing* 16, 8: 1039-1049.
23. Michael W. Levine and Jeremy M. Shefner. 2000. *Fundamentals of Sensation and Perception* (3rd. ed.). Oxford University Press.
24. Markus Löchtefeld, Nadine Lautemann, Sven Gehring, and Antonio Krüger. 2014. ambiPad: enriching mobile digital media with ambient feedback. In *Proceedings of the 16th international conference on Human-computer*

interaction with mobile devices & services (MobileHCI '14), 295-298.

25. Homei Miyashita and Kazushi Nishimoto. 2004. Thermoscore: a new-type musical score with temperature sensation. In *Proceedings of the 2004 Conference on New Interfaces for Musical Expression* (NIME '04), 104-107.
26. Takuji Narumi, Akagawa Tomohiro, Young Ah Seong, and Michitaka Hirose. 2009. Characterizing the Space by thermal feedback through a wearable device. In *Virtual and Mixed Reality*, Randall Shumaker (ed.). Springer Berlin Heidelberg, 355-364.
27. Tal Oron-Gilad, Yael Salzer, and Adi Ronen. 2008. Thermoelectric tactile display based on the thermal grill illusion. In *Haptics: Perception, Devices and Scenarios*, Manuel Ferre (ed.). Springer Berlin Heidelberg, 343-348.
28. Preotiuc-Pietro, D., Schwartz, H.A., Park, G., Eichstaedt, J.C., Kern, M., Ungar, L. and Shulman, E.P., 2016. Modelling Valence and Arousal in Facebook posts. Proceedings of the Workshop on Computational Approaches to Subjectivity, Sentiment and Social Media Analysis (WASSA), NAACL.
29. James A Russell. 1980. A Circumplex Model of Affect. *Journal of Personality and Social Psychology* 39, 6: 1161–1178.
30. Katri Salminen, Veikko Surakka, Jukka Raisamo, Jani Lylykangas, Johannes Pystynen, Roope Raisamo, Kalle Mäkelä, and Teemu Ahmaniemi. 2011. Emotional responses to thermal stimuli. In *Proceedings of the 13th international conference on multimodal interfaces* (ICMI '11), 193-196.
31. Katsunari Sato and Takashi Maeno. 2012. Presentation of sudden temperature change using spatially divided warm and cool stimuli. In *Haptics: Perception, Devices, Mobility, and Communication*, Poika Isokoski and Jukka Springare (eds.). Springer Berlin Heidelberg, 457-468.
32. Katja Suhonen, Sebastian Müller, Jussi Rantala, Kaisa Väänänen-Vainio-Mattila, Roope Raisamo, and Vuokko Lantz. 2012. Haptically augmented remote speech communication: a study of user practices and experiences. In *Proceedings of the 7th Nordic Conference on Human-Computer Interaction: Making Sense Through Design* (NordiCHI '12), 361-369.
33. Eun-Jung Sung, Seung-Schik Yoo, Hyo Woon Yoon, Sung-Suk Oh, Yeji Han, and Hyun Wook Park. Brain activation related to affective dimension during thermal stimulation in humans: a functional magnetic resonance imaging study. 2007. *International Journal of Neuroscience* 117, 7: 1011-1027.
34. Caroline Tagg. 2009. *A corpus linguistics study of SMS text messaging*. Ph.D Dissertation. The University of Birmingham, Birmingham, UK.
35. Cati Vaucelle, Leonardo Bonanni, and Hiroshi Ishii. 2009. Design of haptic interfaces for therapy. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '09), 467-470.
36. Ryuji Watanabe, Ryuta Okazaki, and Hiroyuki Kajimoto. 2014. Mutual referral of thermal sensation between two thermal-tactile stimuli. In *Haptics Symposium* (HAPTICS ‘14), 299-302.
37. Lawrence E. Williams, and John A. Bargh. 2008. Experiencing physical warmth promotes interpersonal warmth. *Science* 322, 5901: 606-607.
38. Graham Alasdair Wilson. 2013. *Using pressure input and thermal feedback to broaden haptic interaction with mobile devices.* Ph.D Dissertation. University of Glasgow, UK.
39. Graham Wilson, Stephen Brewster, Martin Halvey, and Stephen Hughes. 2012. Thermal icons: evaluating structured thermal feedback for mobile interaction. In *Proceedings of the 14th International Conference on Human-Computer Interaction with Mobile Devices and Services* (MobileHCI '12), 309-312.
40. Graham Wilson, Gavin Davidson, and Stephen A. Brewster. 2015. In the heat of the moment: subjective interpretations of thermal feedback during interaction. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (CHI’ 15), 2063-2072.
41. Graham Wilson, Dobromir Dobrev, and Stephen A. Brewster. 2016. Hot Under the Collar: Mapping Thermal Feedback to Dimensional Models of Emotion. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (CHI '16), 4838-4849.
42. Graham Wilson, Martin Halvey, Stephen A. Brewster, and Stephen A. Hughes. 2011. Some like it hot: thermal feedback for mobile devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '11), 2555-2564.
43. Chen-Bo Zhong and Geoffrey J. Leonardelli. 2008. Cold and lonely does social exclusion literally feel cold?. *Psychological Science* 19, 9: 838-842.