# Hot Under the Collar: Mapping Thermal Feedback to Dimensional Models of Emotion

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## ABSTRACT
There are inherent associations between temperature and emotion in language, cognition and subjective experience [22,42]. However, there exists no systematic mapping of thermal feedback to models of emotion that could be used by designers and users to convey a range of emotions in HCI. A common way of classifying emotions and quantifying emotional experience is through ratings along valence and arousal dimensions, originating from Russell's circumplex model [32]. Therefore, the research in this paper mapped subjective ratings of a range of thermal stimuli to the circumplex model to understand the range of emotions that might be conveyed through thermal feedback. However, as the suitability of the model varies depending on the type of emotional stimuli [31], we also compared the goodness of fit of ratings between the circumplex and vector [8,31] models of emotion. The results showed that thermal feedback was interpreted as representing a limited range of emotions concentrated in just two quadrants or categories of the circumplex: high valence, low arousal and low valence, high arousal. Warm stimuli were perceived as more pleasant/positive than cool stimuli and altering either the rate or extent of temperature change affected both valence and arousal axes simultaneously. The results showed a significantly better fit to a vector model than to the circumplex.

## Author Keywords
Thermal feedback; emotion; interaction design.

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

## INTRODUCTION
There are inherent links between emotion and thermal sensation and so thermal sensation is a key component of the conceptualisation and experience of emotion: physical warmth increases interpersonal warmth [22,42] and the experience of physical temperatures helps to ground and process emotional experience [23]. Research has started to look at thermal feedback and emotion in HCI, including the measurement of physiological emotional responses [34,35], the modulating effect of thermal feedback on perception of emotional media [17] and users' inherent interpretations of thermal changes [25,43]. The subjective comfort and intensity of different thermal stimuli have also been measured, but not in the specific context of affective computing [18,44]. However, there is still relatively little work in HCI on thermal feedback and none has yet investigated how thermal sensation maps to common models of emotion, and so how thermal feedback might be classified and utilised to convey different emotions. Being able to convey emotion in HCI is important, to increase engagement, enjoyment and information bandwidth.

The circumplex model of emotion [32] (Figure 1) contends that the majority of emotional experience can be categorised along the two dimensions of *valence* (pleasantness) and *arousal* (excitedness). Emotions are placed in a circular pattern around the two axes and typically split into four umbrella quadrants/categories of low/high arousal and low/high valence. There are databases of images [24] and sounds [4,7] that have been mapped to the circumplex model and used to elicit or convey a range of emotions inside and outside of HCI. Salminen *et al.* [33] were the first to map tactile sensations to dimensional models in HCI, and others have since mapped a range of vibrotactile stimuli to the circumplex [1,28,37,45,46]. The research in this paper is the first attempt to do the same for thermal stimuli. Doing so will show how different emotions and emotion categories might be conveyed using thermal feedback.

Despite the popularity of the circumplex model, several researchers have questioned its validity and how well it actually represents emotional experience [13,31]: for example it cannot represent or account for emotional intensity [29]. Rubin & Talarico [31] have also questioned whether it is always the best for understanding how emotion is classified or structured. Vector models [6,8] (Figures 2 and 3, right) propose that emotions are placed along two straight (or Gaussian [9]) lines emanating from a state of low arousal and neutral valence, which move towards either positive or negative valence as arousal increases. The vector model makes several different predictions to the circumplex [31]. Firstly, emotions vary little in valence at low levels of arousal but the valence range increases with arousal. Secondly, the model predicts that there is no such thing as a


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high-arousal neutral emotion. Finally, it predicts that there are no very high/low valence emotions with low arousal. In comparison to the circumplex, this would mean fewer emotions lie in the two low-arousal quadrants, with most low-arousal stimuli clustered around the vertical axis.

Research has suggested that the suitability of the circumplex varies depending on the type of stimuli used to elicit emotions [13,30,31]. A distinction has also been made between experienced emotion and previously experienced or conceptualized emotions [14], in terms of the factors that contribute to emotional reports [30]: experienced emotion is episodic, experiential, and contextual while beliefs about emotion are semantic, conceptual, and decontextualized. Finally, it has been suggested that abstract stimuli cannot effectively elicit the experience of emotion [6], as they bear no relation to the real stimuli that cause emotion (e.g., view of snarling dog). We hypothesise that rating the emotional content (valence/arousal) being conveyed by thermal feedback is different to rating the internal emotional experience that the circumplex model was formulated to map, and so arousal/valence ratings of thermal stimuli may not accurately fit the circumplex model. This would mean that it might not be possible to represent the full emotional space in thermal stimuli in HCI. This may also be true when using abstract vibrotactile feedback for conveying emotion [1,28,37,45], as the distribution of vibrotactile stimuli in Yoo *et al.* [46] looks to fit a vector model, and even the aforementioned image [24] and sound [4,7] databases tend to lack stimuli in the low-arousal quadrants. Because the circumplex might not be suitable, we compared how well the emotional ratings of thermal feedback fit into a vector model compared to a circumplex.

This paper reports a study where participants received a number of warming and cooling thermal stimuli to the palm of the hand and were told to interpret the stimuli as communicating emotion. They were then asked to rate the meaning in terms of valence and arousal. These ratings were then separately mapped to both the circumplex and vector models [31] to identify which model provided the better fit for this kind of emotional stimuli.

## RELATED RESEARCH

### Thermal Sensation and Emotional Experience

Research has shown a strong, or even inextricable, link between emotional experience and the physical or conceptual experience of "warmth". Attachment theorists stress the importance of physical contact with caregivers (and the concomitant warmth [19]) for the proper social and psychological development of infants [5]. In the field of social cognition, a seminal study by Asch [3] identified associations of personality traits to the words "warm" and "cold". "Warm" was associated with words such as "generosity", "happiness", "humor" and "sociability" (among others), with "cold" associated with the opposite traits. Subsequent social cognition research has suggested that "warmth" is a judgement of another person's perceived *intent*, and includes traits such as "friendliness", "sincerity", "trustworthiness" and "morality" [12,42]. The research argues that "warmth" is the primary of two universal dimensions of social cognition, along with "competence" (the perceived ability of the person to act on traits).

It has been suggested that the term "warmth" is used for such traits because these concrete physical experiences, particularly when young, help to process and ground abstract experiences/concepts such as love, friendliness *etc.* [23]. These inextricable links then stay with us throughout adulthood. Williams & Bargh [42] discussed research showing similar brain activations are associated with both physical warmth and feelings of trust, empathy and guilt. They then went on to conduct a study that found that holding a warm cup of coffee led to judging a target person as having "warmer" personality traits, compared to when holding a cold cup. In another study, Ijzerman & Semin [22] found that holding a warm cup or standing in a warmer room (compared to a colder cup/room), led to higher ratings of social proximity (degree of overlap in personality).

Finally, different emotions are associated with increased or decreased physiological activation throughout the body [27]. While the research did not measure temperature explicitly, increased activity results in increased blood-flow, which inherently results in warmer temperature at the site. Nummenmaa *et al.* [27] found that (de)activation patterns for 14 different emotions were consistent across participants and cultures (Finnish vs. Taiwanese). Increased activation in the head and trunk was associated with anger, fear, happiness, love and pride. Decreased activity was most associated with the arms and legs during negative emotions, such as sadness, anxiety, depression and shame.

The research discussed in this section shows that thermal sensation is a hugely important component of the conceptualisation and experience of emotion. The use of thermal feedback to convey emotions in HCI is, therefore, of great interest and the research reported in this paper begins to systematically map how thermal feedback is associated with emotional experience.

### Dimensional Models of Emotion

The circumplex model of affect [32] is commonly used in emotion research and states that the majority of emotions (or the majority of variance in emotional experience) can be measured/explained in terms of just two dimensions: arousal (physiological activation) and valence (emotional pleasantness). The model is typically visualised with valence along the horizontal axis (negative to the left, positive to the right) and arousal along the vertical axis (low at the bottom and high at the top). The emotions are placed in a continuous circle, centred on a state of moderate arousal and neutral valence (Figure 1), with emotions close to each other being related. The four general categories (quadrants) of emotion are therefore: 1) *high valence, high arousal* (top-right) representing excited pleasant emotions such as happiness and excitement; 2) *high valence, low arousal* (bottom-right) representing calm pleasant emotions such as contentment and satisfaction; 3) *low valence, low arousal* (bottom-left) representing unpleasant calm emotions such as sadness and boredom; and 4) *low valence, high arousal* (top-left) representing unpleasant excited emotions such as anger and frustration. Russell [32] showed that this structure held for how people structure emotion on a general cognitive level, as well as the self-reported internal experience of emotion across participants.

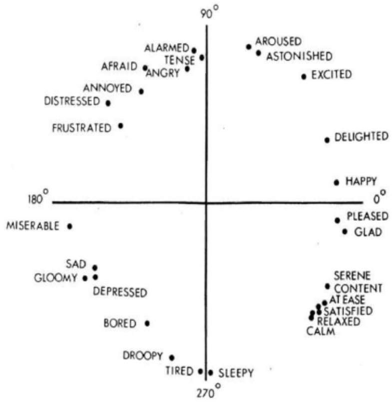


**Figure 1: Original mapping of emotions to a circumplex along valence (x-axis) and arousal (y-axis) dimensions (from [32]).**

However, tactile stimuli, such as temperature or vibration, are abstract and may not have clear emotional content, unlike emotional words, facial expressions or vocal ‘affective bursts’ [4,36]. Touching or moving another person’s body has been shown to be capable of conveying emotions [20,21], but the accuracy is highly variable. Also, while physical touching is a real act associated with some emotions (e.g., hugging, pushing away or stroking) vibration is artificial and disassociated with real emotional expression. Therefore, it is necessary to know if more abstract emotional stimuli are still processed/interpreted in relation to the circumplex. This paper sought to answer 1) can thermal feedback convey the full range of emotions and 2) does the range of emotions available better fit a vector model?

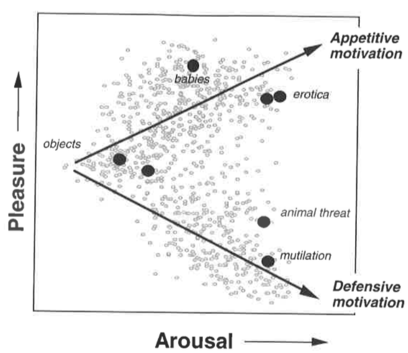


**Figure 2: The distribution of pleasure (valence)-arousal ratings for images in the IAPS [6], illustrating the vector model.**

The vector model of emotion [6,8,31] still suggests that emotions are structured/experienced in terms of arousal and valence, but that they are not continuously related or evenly distributed along the two dimensions. As illustrated in Figure 2 and Figure 3, right, the space starts from a position of low arousal and neutral valence (“pleasure” in [6]), essentially a resting state. At this level of arousal there is a narrow range of possible valences, so there are no very positive (e.g., satisfied) or very negative (depressed) emotions with low arousal. As arousal increases, there are two separate vectors along which emotions lie: one running to very positive valence and one to very negative valence. The two vectors are associated with two fundamental human motive systems: “appetitive” (positive valence, related to sustenance and procreation) and “defensive” (negative valence, related to threat and attack) [6]. Unlike the continuous circumplex model, the two vectors are separate and there is no full range of emotional valence at high arousal. This model predicts that there are no high-arousal neutral emotions, an assertion supported by Rubin & Talarico [31].

The images in Figure 3 show Rubin & Talarico’s [31] instantiations of the circumplex and vector models in order to clarify the differences. In their study, they looked at valence and arousal ratings for three different types of emotional stimuli in increasing degrees of abstraction: written emotional words, generic emotional events and specific autobiographical events. In each case, participants were asked to ruminate on the emotion/event in question and provide ratings for how they felt. Rubin & Talarico then compared how well the ratings fit the circumplex and vector models and established that the vector model proved a better fit for both of the event stimuli, but both models were comparable for the emotional words, which were the stimuli that the circumplex model was based on. The authors concluded that emotional categorization or classification depends on the specific stimulus used to elicit emotion [31].

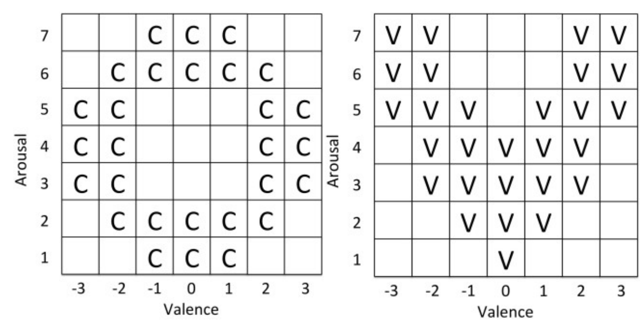


**Figure 3: Generic instantiations of the circumplex (left) and vector (right) dimensional models (from [31]).**

The Positive Affect-Negative Affect (PANA) model [41] shares similarities with the vector model, as positive and negative affect are considered independent axes (not opposite poles of the same axis) and most emotional categories are placed at high arousal states, with few emotions arising from the low-arousal states, that the authors refer to as a “relative absence of affective involvement” (p. 221). Watson & Tellegen [41] suggest the common valence (“pleasantness”) and arousal (“engagement”) axes sit at 45° rotation to the primary horizontal and vertical axes of negative affect and positive affect, respectively. Some research has shown that two dimensions cannot adequately describe enough of the variance in emotional experience, with 4 or more dimensions being necessary [9,13]. However, the number of dimensions necessary to map emotions "depends on the question the researcher is asking" ([13] p. 1056). There are discrepancies in dimensionality when reporting a current emotion compared to previously experienced or conceptualized emotions [30] and we hypothesise that the abstract nature of thermal feedback, compared to facial expressions or emotion words, represents a different type of emotional content. We are therefore asking the question "how do emotional ratings of thermal feedback map to commonly used two-dimensional models"?

### Valence & Arousal Ratings of Tactile Feedback in HCI

Emotional communication is primarily visual, with facial expressions and body movements used to produce or convey emotion much more than physical touch [2,11]. Touch can better convey some emotions, particularly "intimate-relationship" or "pro-social" emotions such as love, sympathy and gratitude [2,20,21]. Non-visual emotional channels have been investigated in HCI under the motivations of 1) incorporating emotional content into common non-visual mobile phone notifications (e.g. [34,37,46]) and 2) providing more engaging multimodal (visual + non-visual) emotional communication (e.g. [1,17,28]). However, research that has sought to convey emotions non-visually has typically used abstract vibrotactile stimuli [1,28,37,45,46].

As we are focussing on mapping thermal stimuli to dimensional models, we limit the discussion to HCI research that has specifically measured valence and arousal ratings (or comparable) for tactile stimuli. In this way, we can compare the ratings/mapping of thermal stimuli to those from existing tactile feedback methods. Useful research has looked at hedonic responses to thermal feedback in communication [15,25,39,40] and during different interactions [43], but the results were more qualitative and did not include mappings to emotional models.

#### *Thermal Feedback*

Salminen *et al.* [34] presented participants with ± 4°C changes from measured skin temperature, or simply skin temperature itself, under two presentation methods: 1) a *pre-adjusted* method, where the stimulator was changed by 4°C before the participant touched it, and 2) a *dynamic* method, where the participant touched the stimulator while it changed. Participants rated the stimuli in terms of pleasantness (synonym of valence), approachability and dominance, and their own arousal, on 9-point scales (-4 to +4). Comparing warm vs. cool and *pre-adjusted* vs. *dynamic* methods, there were no differences in either pleasantness or approachability. Pleasantness ratings for both methods of warming and cooling were around 0 (middle score) and neutral stimuli were slightly more pleasant. In general, both warming methods led to higher arousal and dominance ratings than neutral or cold stimuli. Salminen *et al.* [35] later expanded the number of thermal stimuli being rated to include ±2, 4 and 6°C, but they found similar rating patterns, as warm changes were less pleasant and more arousing than cold changes and larger changes were more arousing and less pleasant. However, they do not report any specific valence-arousal values, and so it is not possible to know where each stimulus sits within dimensional models and so what emotions they may relate to. We extend the existing research by 1) testing a wider range of stimuli, 2) reporting all rating values, 3) placing the values within a visualisation of the circumplex and 4) comparing the fit of values to two dimensional models.

Research has measured the subjective "intensity" and "comfort" of warming and cooling thermal stimuli of ±1°C, ±3°C and ±6°C at rates of change (ROC) of 1°C/sec and 3°C/sec [18,44]. These studies were not related to emotion specifically, only the detection of different stimuli, however the labels are close to those of "arousal" and "valence", respectively. Using 7-point Likert scales, they found that warm, large or fast changes were more intense and less comfortable than cool, small or slow changes. This pattern held when participants were sitting or walking indoors [44] or sitting outdoors [18]. It is important to note that these four studies [18,34,35,44] specifically asked participants to rate the *stimulus* itself along the emotional scales, not any perceived emotional meaning conveyed by the stimulus. This is important because an external stimulus (e.g., thermal or tactile) could be a pleasant or comfortable sensation, such as a cooling breeze on a hot day, yet in a different interpretive context, cold legs/arms can be associated with negative emotions [27].

Halvey *et al.* [17] presented thermal stimuli in conjunction with images (International Affective Picture System (IAPS) [24]) or music, and measured valence and arousal ratings to test any modulating effect of slow (1°C/sec) and fast (3°C/sec) warm or cool changes (±6°C) on the emotional reaction to media. Participants were to rate their own emotional experience and not the stimulus. During the IAPS study, the cold stimulus and fast ROC resulted in significantly more negative valence than a neutral stimulus. Other than this, warming and cooling changes had similar effects on emotional responses to images, but the direction of change was more influential than ROC. Thermal stimuli had no evident effect on emotional reaction to music.

#### *Vibrotactile Feedback*

There has been comparatively more research on mapping emotional meaning to vibrotactile feedback, given its ubiquity in mobile devices. As such, the research forms a baseline against which to compare the more nascent thermal feedback literature, including the results in this paper. While they did not use vibration, Salminen et al. [33] were the first to take valence-arousal (and dominance) ratings for tactile stimuli, specifically skin stretch/friction from a bar rotating at the fingertip. Repeated rotations in the same direction were more pleasant and less arousing than alternating directions, particularly compared to those with regular ("continuous") timing.

Research has looked at the influence of vibrotactile rhythm or duration [1,28,37,46], frequency [1,28,37,46], intensity or amplitude [1,28,37,46], waveform [1,37,46] and spatial movement [28] on valence/arousal ratings of stimuli. Stimuli made up of short or quick constituent pulses are highly arousing [28,37] but longer overall patterns also increase arousal [37,46]. Frequency and intensity have similar influences on emotional ratings but they affect both valence and arousal at the same time: increasing either parameter increases both valence and arousal [1,28,37,46]. Using "rougher" [37] or "fluttering" [46] envelopes or waveforms increases arousal and decreases valence.

Yoo *et al.* [46] have done the most in-depth mapping of vibrotactile stimuli to the circumplex model of affect. Importantly, the study also appears to be the only one to ask participants to rate the emotion being *represented* by the stimulus and not rating the *stimulus* itself. They varied the amplitude (5 values), frequency (60, 100, 150, 200 & 300Hz), duration (50, 100, 300, 500, 1000, 2000ms) and envelope frequency (0, 1, 2, 4, 8, 16Hz). The valence and arousal ratings for all the stimuli presented are shown in Figure 4, along with the emotion labels associated with the relevant positions in the circumplex model [32].

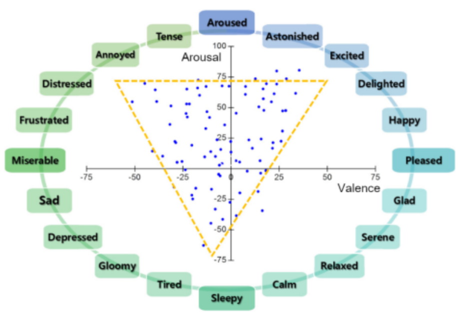


**Figure 4: The mapping of valence-arousal ratings of vibrotactile stimuli to the circumplex from Yoo *et al.* [46].**

As can be seen from Figure 4, the distribution of stimuli is not circular. This suggests that either 1) the range of vibrotactile stimuli chosen were not suitable for conveying low arousal emotions or 2) given the wide range of tactile parameters and values used, vibrotactile stimulation in general may not be capable of conveying a full range of emotions. Following Rubin & Talarico's [31] suggestion that model suitability varies with emotional stimuli, an alternative way of interpreting the second possibility is that the perceived emotions being conveyed from abstract tactile stimuli do not match a circumplex model. Comparing the distribution to the vector model (Figures 2 and 3, right) shows similarities, including a narrow range of low arousal emotions and increasing valence range as arousal increases. In contrast, some stimuli from Yoo *et al.* [46] *did* fit into the neutral valence-high arousal space, which the vector model states should not exist.

As the research in this paper is the first to attempt a mapping of thermal feedback to dimensional models of emotion, we wanted to take Rubin & Talarico's [31] findings into account and compare how well valence and arousal ratings map to both the circumplex and vector models, particularly given the distribution found by Yoo *et al.* [46] and the lack of low arousal tactile stimuli in other research [1,28,37]. This is important, as it will show what range of emotions it is possible to convey with thermal feedback, but it might also indicate the suitability of using the circumplex model in HCI research that attempts to convey emotion.

## EXPERIMENTAL DESIGN

Twenty participants (12M, 8 F) aged 18 to 32 (mean = 23) took part and were paid £10 for a ~40min study. During the study, participants were presented with a range of warm and cool thermal stimuli that they were told convey emotion and were asked to rate the emotion in terms of "arousal" and "valence".

### Thermal Apparatus & Stimuli

The thermal stimulation was provided by two $2cm^2$ Peltier modules [43] (Figure 5) controlled over USB from a host PC running the experimental software. The Peltiers were placed on a desk facing up and the participants rested the palm of their hand on top. The stimuli varied in the *direction* of change (warming and cooling), *rate of change* (ROC; 1°C/sec and 3°C/sec) and the *extent of change* (2°C, 4°C, 6°C and 8°C) from a 30°C neutral starting temperature [38]. This gave a total of 16 stimuli, which were presented twice in a random order during each condition. Each stimulus was presented for 10 seconds and the Peltiers were returned to 30°C for 30 seconds in between each stimulus. This is common practice (e.g., [16,44]), to avoid the effects of skin temperature on thermal perception.

**Figure 5: Peltier devices used (2 x $2cm^2$), with black heatsinks.**

### Experimental Procedure & Measures

Because we believe that the 'target' of subjective ratings (i.e. the stimulus vs. the emotion conveyed) is important and can influence ratings, we include the wording given to participants to explain the experiment for clarity: "*This study will measure what emotional content you think is being represented by the stimulus. The emotional content will be measured in terms of the 'arousal' and 'valence' of the emotion*". Arousal was said to refer to "*physiological arousal or excitedness: a low value indicates calm while a high value indicates excited*" and valence was "*emotional pleasantness: a low value indicates unpleasant emotion while a high value indicates pleasant emotion*". The emphasis was placed on interpreting the emotion being conveyed by the stimulus, not judging the intensity/pleasantness of the stimulus itself.

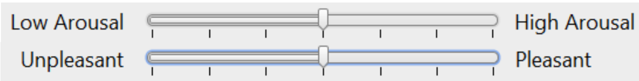


**Figure 6: Rating scales shown in experimental interface for arousal (top) and valence (bottom).**

Following the explanation, the participant rested the palm of his/her dominant hand on the Peltiers, which were then set to neutral 30°C for 30 seconds to adapt the skin to the starting temperature. Following adaptation, the first stimulus selected at random was presented for 10 seconds. After the 10 seconds, the two rating scales (arousal and valence; Figure 6) were presented for the participant to complete and the Peltiers were returned to neutral for 30 sec. Both scales were 7-point sliders with no numerical values, only two anchor labels at either end: "low/high" for arousal and "unpleasant/pleasant" for valence. Upon clicking a "submit" button, the next random stimulus was presented and this continued until all 16 stimuli had been presented twice. The Independent Variables were *Direction* (warm and cool), *Extent of Change* (2°C, 4°C, 6°C and 8°C) and *Rate of Change* (1°C /sec and 3°C /sec). The Dependent Variables were 7-point *Arousal* and *Valence* ratings, which were converted to -3 to +3.

## RESULTS

### The Effect of Gender

There can be large differences in the interpretation of emotion depending on the gender of the interpreter [4,10], although other researchers have found no gender effect [20,21]. Therefore, we first analysed the results to look for any effect of gender on the arousal and valence data separately. Two Mixed-Model ANOVAs were run with *Direction*, *Extent* and *ROC* as within-subjects factors and *Gender* as between-subjects factor. Neither found a main effect of *Gender* nor any interaction effects, and so we combined the data for both genders for the rest of the analysis.

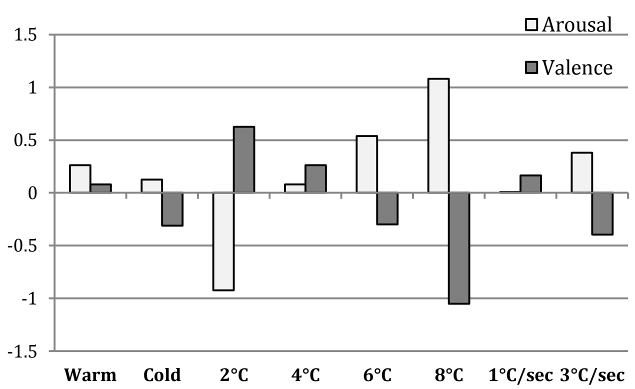


**Figure 7: Average ratings for each thermal parameter.**

### Mapping Responses to the Circumplex Model

The average arousal and valence values for each thermal parameter are shown in Figure 7. Figure 8 shows the mapping of the average values for each individual stimulus to the dimensional model, while Figure 9 maps each thermal parameter. In Figure 8, red marks indicate warming stimuli (above 30°C) and blue marks indicate cooling stimuli (below 30°C). The text labels indicate the extent of change and rate of change ("S" = slow 1°C/sec, "F" = fast 3°C/sec).

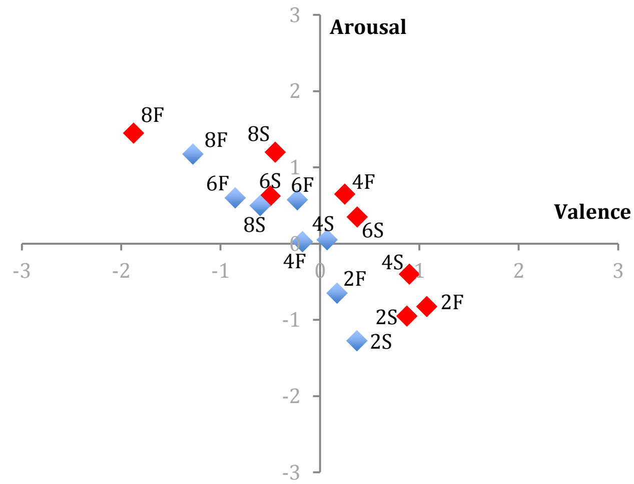


**Figure 8: Distribution of stimuli along both axes. Stimulus details in labels: 2 to 8 = Extent; S = Slow ROC, F = Fast; red = warm up from 30°C, blue = cool down from 30°C.**

The majority of stimuli sit within the 'high arousal, low valence' quadrant (top-left), associated with emotions such as anger, frustration or annoyance, and the 'low arousal, high valence' quadrant (bottom-right), associated with states such as satisfaction or calm [32]. There are a small number of points in 'high arousal, high valence' (top-right; happy, excited) but essentially no points sit within the 'low arousal, low valence' quadrant (bottom-left; depressed, sad, tired). This suggests that thermal feedback alone may only be suitable for conveying calm, positive emotions or excited, negative emotions. To investigate the influence of each thermal parameter on emotional ratings, we ran 2 (*Direction*) x 4 (*Extent*) x 2 (*ROC*) repeated-measures ANOVA on the arousal and valence data separately ($\eta_p^2$ = effect size).

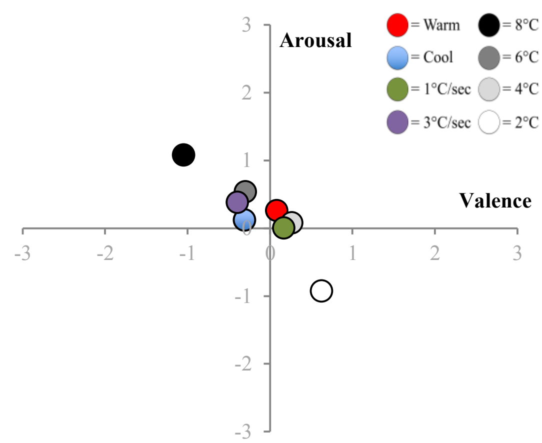


**Figure 9: Mean valence-arousal ratings for each individual thermal feedback parameter (colour/shading).**

There was no main effect of *Direction* on "arousal" ratings, with means of 0.26 (SD = 1.69) for warm and 0.12 (1.87) for cold. There was a significant effect of *Extent* on arousal ratings ($F_{(3, 117)} = 32.402$, $p<0.001$, $\eta_p^2 = 0.45$), with each *Extent* differing significantly from each other. Arousal ratings increased as *Extent* increased with means of -0.9 (SD = 1.56), 0.08 (1.58), 0.53 (1.64) and 1.08 (1.73) for 2°C, 4°C, 6°C and 8°C, respectively. There was also a significant effect of *ROC* on arousal ($F_{(1, 39)} = 11.23$, $p<0.01$, $\eta_p^2 = 0.22$), with the 3°C/sec *rate* resulting in higher average arousal (0.38, SD = 1.73) than the 1°C/sec *rate* (0.01, sd = 1.79).

Regarding the valence ratings, there was no significant effect of *Direction* on valence ratings with means of 0.08 (sd = 1.75) for warm and -0.31 (1.66) for cool. There was a significant effect of *Extent* ($F_{(3, 117)} = 44.36$, $p<0.001$, $\eta_p^2 = 0.53$). Valence ratings decreased as *Extent* increased with significant differences between all pairs, except 6°C vs. 8°C. Means were 0.62 (sd = 1.38), 0.26 (1.51), -0.3 (1.80) and -1.05 (1.68) for 2°C to 8°C, respectively. Finally, there was a significant effect of *ROC* on valence ($F_{(1, 39)} = 35.57$, $p<0.001$, $\eta_p^2 = 0.48$): 3°C/sec resulted in negative, or unpleasant, valence (-0.40, sd = 1.77) while 1°C/sec led to positive, or pleasant, valence (0.16, sd = 1.62).

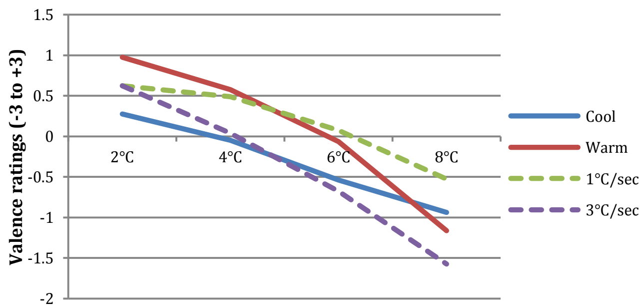


**Figure 10: Interactions between Extent and both Direction (solid) and ROC (dashed) on valence.**

There was a significant *Direction* * *Extent* interaction effect ($F_{(3, 117)} = 3.97$, $p=0.01$, $\eta_p^2 = 0.09$; see Figure 10, solid lines). As *Extent* increases, the valence of warm stimuli drops (becomes more unpleasant) more rapidly than cool stimuli. There was also a significant interaction effect between *ROC* and *Extent* ($F_{(3, 117)} = 5.07$, $p<0.01$, $\eta_p^2 = 0.011$; Figure 10, dashed lines). At 2°C, both *ROCs* result in similar valence but, as *Extent* increases, valence drops more rapidly (becomes more unpleasant) under the 3°C/sec rate.

### How Thermal Parameters Influence Perceived Emotion

Figures 7 and 9 show the overall average “arousal-valence” values for each level of each thermal parameter. As can be seen, warm and slow-changing stimuli are generally interpreted as slightly positive/pleasant (valence) and cool and fast changes are interpreted as slightly negative/unpleasant. As the *Extent of change* increases, however, both valence and arousal ratings change in combination. It is important to know how changing a single parameter or level might influence the perceived emotion, to understand better how to access as full a range of emotions as possible. Figures 11 to 13 show the distributions of all stimuli from Figure 8 with arrows indicating the effect of changing only the *Direction* (Figure 11), *Extent* (Figure 12) or *ROC* (Figure 13). Figure 11 shows that, at smaller and slower changes, changing the *Direction* predominantly changes the valence of the stimulus: warming increases valence while cooling decreases it. However, at greater *Extents* or faster ROC, changing *Direction* increasingly affects arousal. Therefore, the perceived emotion can be made more pleasant by using warmth instead of cooling, or *vice versa* for negative.

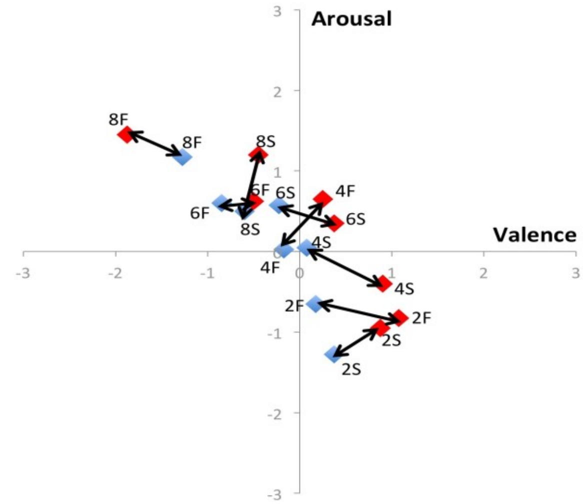


**Figure 11: Arrows indicate the effect of changing the Direction (warm vs. cool) of a stimulus with the same Extent and ROC. Stimulus details in labels, as in Figure 8.**

The effects of changing either *Extent* of change (Figure 12) or *ROC* (Figure 13) are similar. At low *Extents* of change (2-4°C), increasing either the *Extent* or *ROC* predominantly acts to increase the arousal of the emotion, while valence reduces slightly. As the *Extent* increases, however, increasing *Extent/ROC* affects valence more. At moderate changes (4-6°C), both valence and arousal change by a similar amount but, at high changes, valence is primarily affected.

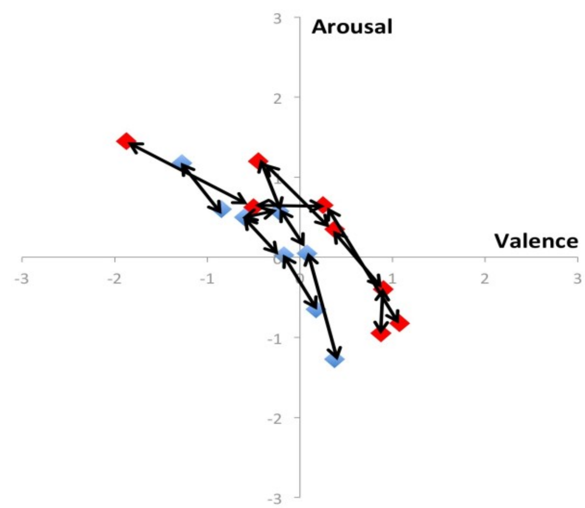


**Figure 12: Arrows indicate the effect of changing by 2°C the Extent of a stimulus with the same Direction and ROC. Stimulus details are omitted for clarity (see Figure 8).**

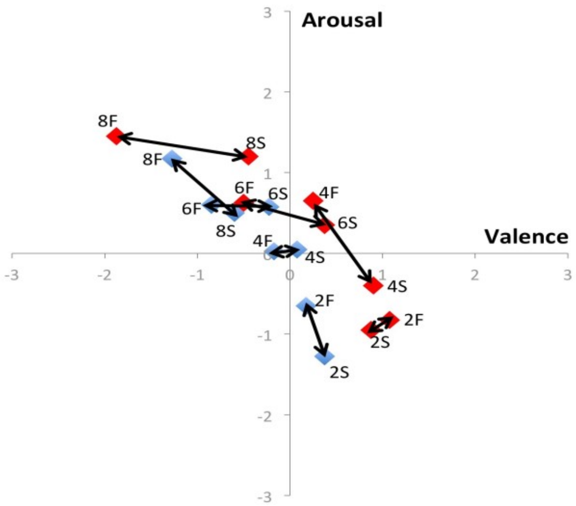


Figure 13: Arrows indicate the effect of changing the ROC of a stimulus with the same Direction and Extent. Stimulus details in labels, as in Figure 8.

### Comparing Fit to Circumplex and Vector Models

The goodness of fit to the two dimensional models was done in the same way as Rubin & Talarico [31]. Using the converted -3 to +3 scales, each arousal and valence pair was taken as a coordinate in the instantiations of the two models shown in Figure 3. If the coordinates fell within the lettered squares (indicating a fit with the model) the trial was given a value of 1, otherwise it was given 0. The average value over all trials within each participant was taken as how well the responses fit each model. A paired-samples t-test was run on the goodness of fit to the two models.

There was a significant difference in the goodness of fit for the circumplex model (mean = 0.55, sd = 0.13) compared to the vector model (mean = 0.76, SD = 0.15); $t(19) = -3.92$, $p = 0.001$. This supports the assertion that the goodness of fit to a dimensional model depends on the emotional stimulus, as the ratings for the emotions being conveyed by thermal stimuli did not fit the traditional circumplex model as well as a vector. Our hypothesis that the ratings would better fit a vector model was supported.

The distribution in Figure 8 clearly show a narrow concentration of values, which is very different from the proposed circumplex in Figure 1. However, there are also several differences to the vector model. We found no low arousal, neutral valence stimuli: the position in the vector model from which the two vectors are proposed to originate. In addition, the distribution only moves along a single vector, diagonally from low arousal, high valence to high arousal-low valence. Given the small number of available parameters and stimuli in thermal feedback, it is likely that the channel by itself cannot convey a full range of emotions. While vibrotactile feedback is abstract, there are more available parameters to manipulate and more available levels for each parameter. This provides a wider range of perceptually different sensations through which to convey a wider range of emotional stimuli [46].

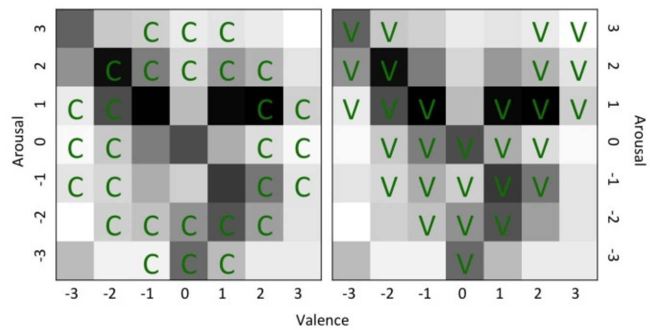


Figure 14: Shading shows number of valence-arousal response pairs falling within each square (darker = more responses). Circumplex (C) and vector (V) model instantiations [31] are superimposed to compare how responses fit.

In Figure 14, the 7 x 7 arousal and valence coordinates from Rubin & Talarico's [31] model instantiations are shown, with the shading in each square indicating the number of participant responses that fell within it (darker shading = more responses). The circumplex and vector instantiations are then superimposed over the same data, to show how the proportion of responses relate to each model. The higher the number of dark squares under each model, the better the fit responses had to that model.

## DISCUSSION

### How Thermal Parameters Influence Emotion

Figures 7 and 9 show the average ratings for each level of each thermal parameter used and Figures 11 to 13 illustrate the effect of changing the level within each thermal parameter. As found in other research [25,43], they show that warm stimuli were perceived as pleasant (positive valence) and cool stimuli were unpleasant (negative) and so, as Figure 11 shows, switching the direction of change (keeping all other parameters constant) from cool to warm results in making the emotion more positive. Conversely changing to cool from warm makes it more negative. However, this pattern only applies to low and moderate thermal changes: changing direction at the highest Extent of change (8°C) results in the opposite effect: warming *decreases* valence.

These results are mostly in contrast to Salminen *et al.* [34,35], who found that small (≤6°C @ 0.5°C/sec) warming stimuli led to higher arousal and were less pleasant than cool stimuli. This may be because participants in these studies were asked to rate the valence of the stimulus but their own arousal ("the stimulus felt un/pleasant", "I felt calm/aroused" [35] p. 24) while we asked participants to rate the perceived emotion being conveyed. Salminen *et al.* [35] did not report valence/arousal values so we cannot compare our results directly. We also used two Peltiers and two ROC (both faster than [34,35]), and area and speed both influence thermal sensation [38].

Changing either the Extent of change or ROC has a similar effect on the perceived emotion (see Figures 12 and 13, respectively): at small to moderate changes (2-4°C) increasing the Extent by 2°C or increasing the ROC mainly results in increasing the perceived arousal of the emotion (and *vice* *versa* for decreasing Extent/ROC). At larger changes of 6-8°C, increasing either Extent or ROC increasingly results in making the perceived emotion more unpleasant (decreasing valence). However, in general, changing Extent/ROC affects changes in both axes at the same time, so it may be difficult to isolate a change in only one dimension, apart from by using direction. These results are in line with Salminen *et al.* [35], who also found that increasing Extent of change increased arousal and decreased valence. Like us, they also found an uneven influence of Direction, as increasing extent had a stronger effect on warm stimuli.

**Dimensional Distribution**

The mappings of each thermal stimulus to arousal-valence ratings are shown in Figure 8, and Figure 15 shows the distribution relative to the proposed emotion positions within the circumplex. There was a fairly limited distribution, with the vast majority of points falling in 1) the high valence, low arousal quadrant (bottom-right) representing calm and pleasant/positive emotions; and 2) low valence, high arousal quadrant (top-left) representing excited and negative/unpleasant emotions. Two warm and one cool stimuli lie just within the top-right quadrant (high valence, high arousal). No stimuli fell within the bottom-left quadrant (low valence, low arousal).

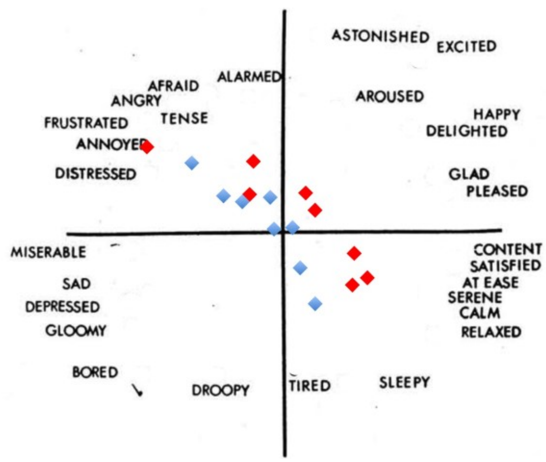


**Figure 15: Distribution of thermal stimuli overlaid on the classic circumplex model, with emotion labels.**

The distributions show that thermal feedback is predominantly interpreted as representing calm and pleasant emotions such as satisfaction or contentment, or excited and unpleasant emotions such as distress, annoyance or anger. These results are consistent with research that found moderate warmth to be associated with positive emotions such as social closeness [22,42,43]. However, warmth has commonly been associated with stronger, more "excited", positive emotions, such as love, gratitude and happiness [5,19,26]. Despite this, very few stimuli fell within the high valence, high arousal quadrant associated with these emotions, and those that did were weakly rated as so, sitting close to the centre of the graph. The stimuli in this quadrant are moderately strong (4°C at 3°C/sec, 6°C at 1°C/sec), with smaller/slower changes sitting in the bottom-right quadrant (feeling calmer) and larger/faster changes sitting in the top-left quadrant (feeling more unpleasant). While warm stimuli act to make the perceived emotion more positive, it may be that the range of available (comfortable) warm temperatures is too narrow to access more of the top-right quadrant. Or, as is discussed below, the area/location of stimulation may be a limiting factor.

The remaining stimuli sit within the top-left quadrant (excited and unpleasant emotions). Most of these stimuli are cool changes but the others are the fastest and hottest changes. Anger is commonly associated with heat in the English language (e.g., "burning rage", "simmering anger", "hot headed") and anger, fear and disgust (which sit within the same quadrant in the circumplex model [32]) are all associated with increased bodily activation, which also results in increased temperature. However, quite why so many cold stimuli were rated within this quadrant is unclear, especially since no stimuli were placed within the bottom-left quadrant, which represents sadness, depression and boredom. Cold has been strongly associated with negative emotions such as unhappiness and lack of social cohesion in previous research [3,5,22,42,43].

*Comparison of Dimensional Models*

There are three potential explanations for these findings. The first is the simplest, that abstract thermal feedback by itself cannot convey a range of emotions. The second is that a vector model better explains how emotions relate to experienced valence and arousal. Following the analysis procedure of Rubin & Talarico [31], our results showed that the distributions fit a vector model significantly better than a circumplex model. As discussed above, the vector model states that there are no strong unpleasant or pleasant emotions at low levels of arousal, and our distribution showed no strong negative emotions at low arousal and only weak-to-moderate positive emotions. The vector model also states that arousal increases as emotions become more positive/negative and, in our data, as arousal increased, the valence decreased. It therefore resembles something of a one-sided vector model and so, despite the relatively good fit to a vector model (0.75), the evidence does not entirely support our hypothesis that a vector model better represents or explains the emotions that can be conveyed through tactile stimulation.

The second explanation is the evidence that emotional states such as sadness, depression and boredom are characterized not by *low activation* but actually by *deactivation* [27,29]. In both the circumplex and vector models, a resting state consists of no arousal (placed at the bottom of the vertical axis in the circumplex). From here, there is no deactivation, only increasing levels of arousal. Reisenzein [29] instead posits that a resting state sits at a moderate level of arousal. Some emotions then result from an *increase* in activation (e.g., nervousness, anger or joy) while others result in *decreased* activation (such as "gloom" or depression). Bodily deactivation was also associated with sadness and depression in Nummenmaa *et al.* [27]. As discussed above, cold stimuli act to reduce the perceived emotional valence.

However, is it possible for thermal feedback to convey *deactivation*? Like auditory and vibrotactile stimuli, external thermal stimuli applied to the skin can only really vary from *no* stimulation (skin temperature) to a prescribed *maximum* change. The inherent polarity of thermal stimulation (cold vs. warm) is unique, compared to sound or vibration, but it may be that any stimulus provided unavoidably represents activation. If the emotions that researchers place in the bottom-left circumplex quadrant are indeed characterized by deactivation, *HCI may struggle to adequately represent them*. This hypothesis needs to be studied but it is partially supported by some data: our distributions are very similar to that found by Yoo *et al.* [45] with a small number of vibrotactile stimuli. They later increased the number of stimulus parameters and parameter levels and found a wider distribution, including into the top-right quadrant [46]. However, both studies failed to identify stimuli that represented the bottom-left (and bottom-right to an extent) quadrant. It may be that, as different stimuli fit different models, researchers are yet to identify a model that can adequately represent what emotions can be conveyed when producing abstract audio, vibrotactile or thermal feedback in HCI.

### Increasing the Range of Emotions

Given our limited distribution, and the wider range of emotions Yoo *et al.* [46] measured after increasing the number of parameters, it may be worth doing the same with thermal feedback. However, the thermal sense affords fewer available parameters than tactile stimulation, generally just those used in this study (direction, extent and ROC) along with area of stimulation and spatial location. Changing the area of stimulation has a similar effect on thermal sensation as changing either extent or ROC: it increases/decreases the subjective intensity of the stimulation (known as spatial summation) [38]. Therefore, it is possible that changing the area will result in similar changes in perceived emotional meaning as changing extent/ROC (see Figures 12 and 13). However, greater or lesser extents of bodily contact in different locations around the body are used to convey different emotions [20], so increasing the area or changing the spatial location of stimulation may have an effect. A more promising route would be to combine thermal and vibrotactile signals to attempt to access a wider range of emotional meaning, which we will study next.

### Conveying Emotion in HCI Using Thermal Feedback

The research in this paper has shown how different thermal changes might represent different emotional meanings, and so these associations can be used to augment applications with affective information. As touch and temperature are particularly associated with "intimate-relationship" or "pro-social" emotions such as love, sympathy and gratitude [2,20,21] thermal feedback might be well-suited to augmenting social media and SMS. While thermal feedback might not be able to convey a full range of emotions, the research presented here still gives guidance as to how it could be used to influence the perceived affective quality of interactions in HCI. Some research has used thermal [17] or vibrotactile [1,28] feedback to augment the emotional reaction to media (images and music) but the results show that the thermal/tactile feedback has little effect as the visual stimulus (and auditory to a lesser extent) dominates the user's reaction. Affective feedback would be best utilized in interactions that already lack strong emotional content.

General pleasant/positive or unpleasant/negative emotional states could be conveyed through moderate (<=4°C) warm or cold, respectively. Alternatively, a general state of being calm (low arousal) or excited (high arousal) could be reliably conveyed by the use of small (2°C) or large (8°C) changes, respectively, in either direction. Thermal feedback can also convey the two more specific emotional categories of 1) calm and positive (high valence, low arousal) through small (2-4°C) warming changes and 2) excited and negative (low valence, high arousal) through large (6-8°C) warming or cooling changes. However, we cannot yet say that thermal stimuli convey the specific emotions shown near the points in Figure 15.

## LIMITATIONS AND FUTURE WORK

As mentioned above, we only used three thermal parameters (direction, extent and ROC) and only a subset of possible extents and ROCs. In future work we will investigate the effect of spatial location and area of stimulation of thermal feedback on the perceived emotion, to see if they provide a wider range of affects. However, we believe that the best route to conveying a wider range will be to combine feedback channels, and so we will combine thermal with vibrotactile stimuli and also sound. We also need to test whether the stimuli positioned close to emotional terms in Figure 15 are specifically perceived as those emotions, to validate the findings here. Finally, we will investigate whether the use of terms "activation" and "deactivation" instead of "high/low arousal" will lead to a different distribution of stimuli.

## CONCLUSIONS

This paper presents the first mapping of a range of thermal stimuli to dimensional models of emotion, to understand how thermal feedback might be used to convey different emotions. Valence and arousal ratings were taken for the perceived emotion being conveyed by 16 thermal stimuli that varied in direction of change, extent of change and rate of change. The distribution was mostly limited to the high valence, low arousal quadrant (calm, pleasant emotions) and low valence, high arousal quadrant (excited and unpleasant emotions). Warm stimuli were considered more pleasant/positive than cool stimuli, and increasing the extent or rate of change increased arousal and decreased valence. In line with the suggestion that the suitability of the circumplex for modelling emotion varies with different emotional stimuli, we found that the distribution of points better fit a vector model than the circumplex. This suggests that it may be difficult to convey the full range of emotions in the circumplex through thermal feedback alone.

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