The Impact of Thermal Cues on Affective Responses to Emotionally Resonant Vibrations

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ABSTRACT

This paper investigates how presenting emotionally resonant vibrotactile stimuli at cool, neutral and warm temperature levels impacts mean ratings for emotional resonance and affective response. Affective vibrotactile stimuli can elicit pleasant or calming responses, making them applicable for emotion regulation. Evoking real-world sensations via emotional resonance can widen their affective range and improve their effectiveness, and allow them to enhance immersive multimodal experiences. Thermotactile cues have been shown to affect emotional responses, but have not been combined with emotionally resonant vibrations to see how they change responses to such cues. This study (n=20) assessed the impact of 3 temperature levels (24℃, 30℃, and 34℃) on 15 emotionally resonant vibrotactile cues and observed if emotionally resonant stimuli exceeded the affective range non-resonant vibrotactile stimuli. The findings suggest that presenting specific resonant vibrations at temperatures that are appropriate for the sensation they evoke can improve emotional resonance and *vice versa*. In addition, temperature had a positive effect on affective response and emotionally resonant vibrations were found to have a wider affective range than traditional vibrotactile cues. These findings support using emotionally resonant vibrations and thermal cues to elicit desirable emotional responses in emotion regulation and immersive media applications.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; *Haptic devices*; User studies.

KEYWORDS

Affective Haptics; Thermotactile; Vibrotactile; Emotional Resonance

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1 INTRODUCTION

Affective vibrations has seen increased research focus as new techniques for evoking emotional responses are developed and applications like emotion regulation are explored [26, 48, 58]. However, the range of emotions that can be elicited is limited [51, 57]. Emotionally resonant vibrotactile stimuli can elicit a wider range of affective responses than normal vibrotactile waveforms, where the 'emotional resonance' of a stimulus is defined as its ability to evoke real-world phenomena and elicit a related emotional response from the subject experiencing it (e.g. a cat purring vibration reminding the user of past experiences with cats) [27]. Thermal cues can also elicit emotional responses but it is unclear how presenting them simultaneously alongside emotionally resonant vibrations will impact the resultant emotional response or emotional resonance. In particular, does presenting emotionally resonant vibrations at 'appropriate' temperatures (e.g., cold running water) or 'dissonant' temperatures (e.g., a cold heartbeat) significantly reinforce or reduce their resonance? Addressing this question will inform future haptic interfaces which leverage emotionally resonant vibrotactile and thermotactile stimuli to create immersive, pleasant and resonant emotional experiences.

Early affective vibrotactile investigations observed how varying the parameters of amplitude, frequency and rhythm impacted participants' ratings for arousal (how alerting a stimulus was) and valence (how pleasant it was) [38, 41, 57], finding vibrotactile cues possess a narrower valence than arousal range. More recent research explored responses to emotionally resonant stimuli which evoked real-world sensations, like cat purring or rain, to allow vibration to elicit a wider range of more meaningful emotional responses [27, 44]. Affective responses to thermotactile stimuli have been measured, with early work finding that warmth could positively impact arousal and valence [12, 39, 40]. Investigations of emotional responses to simultaneously presented vibrotactile and thermotactile stimuli suggested that thermal cues had more influence on valence, while vibration influenced arousal [48, 51]. There has, however, been no investigation of how combining thermotactile and emotionally resonant vibrotactile cues would impact how resonant participants found the resulting sensations or their emotional responses to them.

Emotionally resonant stimuli can elicit positive and meaningful emotional responses using simple vibrotactile cues and thus their further development has value to the affective haptic field. As

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emotionally resonant stimuli leverage past experiences with real-world phenomena to elicit related emotional responses, thermal cues which reinforce this could make these stimuli more effective, motivating its inclusion in future interfaces for calming emotion regulation or immersive haptic experiences. It is also important to understand if dissonant temperature levels can reduce the effectiveness of emotionally resonant stimuli, which may influence their applicability in different environments. Additionally, as the field of emotionally resonant affective vibrotactile stimuli is still small, only a limited range of sensations have been evoked. Prior work has not observed emotional resonance ratings for each stimulus, or directly compared the affective range of these stimuli to previously explored non-resonant vibrations generated from varying frequency or amplitude. This study will address these limitations.

This paper reports findings from a user study (n=20) which observed emotional responses to the widest set of emotionally resonant vibrotactile stimuli thus far evaluated, along with thermotactile stimuli and the simultaneous presentation of both modalities. Participants rated stimuli based on how pleasant, alerting and emotionally resonant they perceived them to be and discussed their experiences of them in a qualitative interview. The results indicated that, when presented alongside emotionally resonant vibrations, thermotactile stimuli can have a significant impact on participant arousal, a smaller but still significant impact on valence and that presenting specific vibrations alongside expected or dissonant temperature levels can impact their emotional resonance accordingly.

1.1 Contribution Statement

This work makes four contributions: (1) First experimental observation of emotional responses and resonance ratings of combined emotionally resonant vibrotactile and thermotactile stimuli. (2) Improved understanding of the design space for emotionally resonant vibrations through the trial of a larger stimulus set. (3) Demonstration through comparison that emotionally resonant vibrations can exceed the affective range of non-resonant stimuli. (4) Informs how thermal cues can be used to reinforce the emotional resonance and affective responses of vibrotactile stimuli in future applications.

2 RELATED RESEARCH

2.1 Measuring Affective Touch with the Circumplex Model

Emotional responses are commonly measured using Russell's Circumplex Model of Affect [37]. This model maps valence (pleasantness to unpleasantness) and arousal (alerting to non-alerting) to a two-dimensional plot with neutral intersection between both scales. Thus it allows designers and researchers to assess emotional response to affective computer interfaces by taking two self-reported measures. This model is widely used in the assessment of affective haptic interfaces [6, 12, 15, 51, 57] and allows for the external comparison of results. Our work in this paper utilised this emotional modelling approach.

2.2 Affective Vibrotactile Research

Foundational affective studies of vibrotactile stimuli explored how varying waveform parameters like frequency, envelope frequency, amplitude and rhythm impacted emotional response. The majority of findings suggest that amplitude, and as a result intensity, has a positive effect on arousal [3, 15, 51, 57] and a negative impact on valence at all or most levels of frequency [3, 15, 51, 57]. The effects of envelope frequency, the interval between waveform envelope peaks, are less explored, but it has been shown to have both positive [15] and negative effects on valence [15, 57] and while Hasegawa *et al.* found a strong negative impact on arousal [15], Yoo *et al.* found no conclusive effect [57]. Rhythm can also impact affective responses [15, 41], as Seifi *et al.* and Hasegawa *et al.* found longer uninterrupted vibrations were perceived as more pleasant, while shorter stimuli with more pauses were more arousing. Notably, multiple researchers found that vibrotactile stimuli are able to generate a wider range of arousal responses than valence and that areas of the Circumplex Model, particularly low arousal areas, have a notable narrow valence range [15, 27, 51, 57], limiting the ability to elicit a wider range of emotional responses in affective vibrotactile interfaces.

Affective vibrotactile interfaces are increasingly being applied to the field of emotion regulation. Miri *et al.* described how haptic stimuli can regulate emotion in three ways: distraction from internal symptoms, cuing up beneficial thought patterns or using biofeedback to improve response modulation [29]. Wearables delivering heartbeat-like vibrations have been successfully used to elicit calmer emotions and lower heart-rate [5, 7, 8, 36, 54, 58]. Umair *et al.* explored using personalised multimodal patterns to lower stress [48] and vibrotactile biofeedback has been used to regulate breathing and heart-rate [30] or promote emotional closeness during remote communication [31]. By evoking pleasant real-world experiences, emotionally resonant vibrations could enable emotion regulation in two of the ways outlined by Miri *et al.* [29]; by acting as a calming distraction and cuing positive thoughts associated with the sensations they evoke.

Vibrotactile stimuli have been used to enrich the experience of listening to music [16] and to intensify emotional reactions to immersive film experiences [25]. Ahmed *et al.* explored vibrotactile stimuli to mediate affective touch in virtual reality, although they found force feedback a more appropriate solution for that application [1]. Vibrotactile arrays have also successfully been used to simulate the sensation of social stroking and provoke pleasant emotional responses [9, 18]. Future interfaces could build on these works by utilising emotionally resonant vibration to evoke real-world sensations as part of immersive multimodal media experiences.

2.3 Affective Thermotactile Research

Initial research by Salminen *et al.* used temperature levels 4℃ warmer and cooler than the base temperature of the hand and found that warmth increased arousal, but temperature had no effect on valence [39]. They followed up by testing an expanded set of levels, as did Wilson *et al.*, both finding that small and warm shifts were pleasant, larger shifts were unpleasant and both increased arousal [40, 53]. Tewell *et al.* found when presenting thermal cues alongside text messages, temperature strongly impacted arousal but not valence [46]. Other researchers explored augmenting images with thermal cues, finding that temperature could enhance the pleasantness or unpleasantness of affective images, dependent on whether the temperature level was emotionally resonant with the content of the image [2, 13, 33] (e.g. warmth is resonant with the images of hot ramen but not cold ice cream [33]). This highlights the potential for thermal cues to impact responses to emotionally resonant vibrotactile stimuli in a similar manner.

Affective responses to simultaneously presented thermotactile and vibrotactile cues have also been investigated. When combined, researchers found that temperature tended to influence valence, while vibration influenced arousal or urgency [50, 51, 56]. Wilson *et al.* found that, when presented simultaneously, vibration dictated the arousal of the emergent experience, while the thermal component influenced valence, with warmer stimuli being more pleasant [51]. Yoo *et al.* found that a thermal component had the potential to exaggerate emotional responses to vibrotactile stimuli, finding that pleasant vibrations presented at a constant cold temperature were more pleasant and warm unpleasant vibrations become more unpleasant [56]. Shetty *et al.* corroborated that constant temperatures had the potential to emphasise existing affective responses, but found that dynamic shifts in temperature were unpleasant [42]. Umair*et al.*'s qualitative approach found that both warm and cold temperatures could be pleasant based on their meaning to that participant, but that cold was more arousing and more 'unexpected' than warmth [48]. Prior work has also demonstrated that concurrent thermal cues can impact the perception of vibrotactile patterns depending on whether their intensity of pulse duration varied [24]. It is unclear how thermal cues will impact affective responses to emotionally resonant stimuli, if they will be dependent on the sensations being evoked, as it was for affective image augmentation, and whether they could lead to more immersive haptic experiences.

2.4 Emotionally Resonant Haptics

Emotional resonance has been leveraged in affective audio for many years, with multiple study findings suggesting that soundscapes which participants had positive emotional associations with helped them feel less pain and stress in clinical settings [4, 10, 14, 47]. Similar effects have been achieved in public settings, bringing calming soundscapes to urbanised spaces to elicit calmer emotional responses [35, 49].

Vibrotactile actuator arrays have been used to create patterns representative of real-world phenomena like raindrops [22, 34, 44], and Shim *et al.* observed that these can elicit a wide range of related emotional responses [44]. Other haptic interfaces have used texture, sound or visual metaphor to enhance emotional resonance. The Haptic Remembrance book aided care home residents recall past experiences using a book with touch and audio displays which evoked past life events [11]. Iosifyan *et al.* found that emotional associations with certain materials and real-world phenomena, such as granite and gravestones, impacted participant emotional response [21]. Social robot animals, like Paro the seal, aim to evoke interaction with pets to promote similar social and enjoyable behaviours in their users [17, 43, 55].

The potential for emotional resonance to elicit positive, calming or pleasant emotional responses is clear. So far most research has utilised complex haptic interfaces (e.g. tactor arrays, visual and audio displays, or social robots), limiting availability and applicability to new settings. Macdonald *et al.* achieved emotional resonance with single-actuator vibrotactile stimuli [27] and this study directly follows up, using and expanding the same stimulus set, directly measuring emotional resonance alongside affective response and observing how thermal cues impact these responses.

3 USER STUDY: AFFECTIVE RESPONSES TO EMOTIONALLY RESONANT VIBROTACTILE STIMULI ALONGSIDE THERMAL CUES

A within-subjects experiment was designed to observe affective responses to emotionally resonant vibrotactile stimuli presented at three temperature levels. The experiment had two independent variables: the set of vibrotactile stimuli (15 emotionally resonant cues and 9 non-resonant cues) and temperature level (warm, neutral, cold) presented. Three dependent variables were measured: self-reported valence, self-reported arousal and self-reported emotional resonance. We hypothesised that warm thermal cues would have a significant positive effect on valence and arousal, and that the emotional resonance of stimuli with an expected temperature would be impacted by temperature (e.g. *Cat Purring* would be more resonant if presented with warmth, less with cool). Additionally, it was expected that the affective range of the emotionally resonant stimuli set would exceed that of non-resonant stimuli.

3.1 Apparatus

Haptic stimuli were delivered to a participant's palm via a handrest assembled from combining two haptic actuators (see Fig, 1). Vibrotactile stimuli were delivered via a Haptuator Mk II [19] which was attached firmly to the heat-sink of a ThermoElectric Peltier element with electric tape. A foam cover was fashioned to fit around the heat element on top of the device, allowing participants to rest the heel of their palm upon the element and let their fingers drape around the device comfortably. With their hand in this position, participants experienced simultaneous thermal stimulation on their palm from the heating element and vibrotactile stimulation to their hand throughout the device. A circle of thin foam was placed under the device to absorb the vibration and reduce noise pollution and participant wore headphones with brown noise to mask any sound from the vibration actuator. The Peltier was controlled by the laptop via a QUUTEC Quad Universal USB ThermoElectric Controller and the Haptuator was controlled via the Haptu-Amp-Quad board [20]. The laptop used was a 2018 13" 2.3GHz Core i5 MacBook Pro with its internal volume level set to 6 and was used to both deliver the stimuli and record user self-reported ratings for valence, arousal and emotional resonance.

3.2 Experiment Design

3.2.1 Stimuli. The study presented users with three thermal levels. A base level of 30℃ was maintained by the Peltier throughout to keep the skin at a neutral temperature [50–52], except when presenting a cool (24℃) or warm cue (36℃). These ±6℃ levels were chosen to be large, noticeable shifts [53]. Following pilot testing where the warm level was consistently reported as feeling dangerous and unpleasant, it was reduced from 36℃ to 34℃.

15 emotionally resonant vibrotactile stimuli were used. Seven of these were drawn from Macdonald *et al.*'s initial study on single-actuator emotionally resonant vibrations. To this set, a further eight

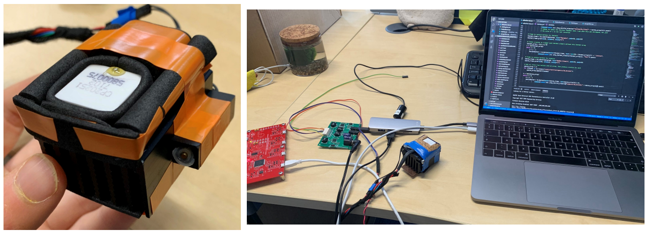

Figure 1: Experimental apparatus used. A Haptuator Mark II was tightly bound to a heatsink and Peltier thermoelectric element to create an all-in-one hand-rest for delivering vibrotactile and thermotactile feedback. The Haptuator was controlled via a Haptu-Amp-Quad and the Peltier via a QUUTEC Quad Universal USB ThermoElectric Controller and a laptop computer.

were added. The new stimuli were chosen based on their ability to display effectively via a single vibrotactile actuator and were drawn from haptic preferences found in prior work [28]: *Raindrops*, *Vacuum Cleaner*, *Scratching*, *Brushing*, *Wind*, *Car Engine*, *Dog Growling* and *Train Tracks*. Acoustic waveforms were sourced from the audio repository Freesound.org [45]. Stimuli were processed following the procedure used in prior work [27]: first, to normalise presentation across different stimuli, a 300Hz low-pass filter was employed to de-emphasise frequencies not well presented by the Haptuator, followed by volume normalisation of 89dB using the program MP3Gain [32]. Stimuli were presented for ten seconds, allowing time for the patterns in the acoustic waveforms present to play out and be recognised. Researchers identified eight stimuli with an 'expected temperature' that the original phenomenon was associated with (e.g. *Cat Purring* was associated with warmth, *Raindrops* with cold) and it was expected that any instances of temperature affecting the resonance of stimuli would occur within this subset. The full set of emotionally resonant stimuli and their expected temperatures, if applicable, is listed in Table 1. The set of nine non-resonant vibrotactile stimuli, presented for comparison of affective range, were created by varying three levels of frequency and amplitude and were identical to those used in multiple past affective haptic studies [27, 51, 57] (see Table 2). These were also presented for ten seconds.

Emotionally Resonant Stimuli (with expected temperature if present)		
Cat Purring* (Warm)	Raindrops (Cold)	Brushing
Slow Breathing*	Small Stream* (Cold)	Crashing Waves* (Cold)
Dog Growling	Vacuum Cleaner	Car Engine (Warm)
Wind (Cold)	Muffled Conversation*	Train Tracks
Heartbeat* (Warm)	Underwater Bubbles* (Cold)	Scratching

Table 1: Table listing all the full set of emotionally resonant vibrotactile stimuli presented. Seven stimuli were assigned an expected temperature that may be associated with the original sensation. * indicates the stimulus was used in prior work [27]

Parameter	**Values**
Amplitude	A1,A2,A3
Frequency	F1,F2,F3

	A1	**A2**	**A3**
F1: 90Hz	1.7g	3.3g	4.3g
F2: 200Hz	0.6g	1.0g	1.3g
F3: 300Hz	0.9g	1.2g	2.2g

Table 2: Frequency and amplitude levels used to generate the nine non-resonant vibrotactile stimuli presented in Task 1 and 3. Amplitude levels were adjusted for different levels of frequency to normalise perceived intensity [51, 57] (g = gravitational acceleration).

3.2.2 Participants. 20 participants (11 male, 8 female, 1 non-binary) were recruited using university, email and social media channels. Participants were required to be at least 18 years old and have full haptic perception in their hands.

3.2.3 Experiment Procedure. The experiment took place in a lab with a table, chair, laptop computer and the haptic hand-rest. Participants were paid a £10 Amazon voucher for their participation which took approximately fifty minutes. Participants read an information sheet and signed a consent form to proceed with the experiment. The experiment was structured into three tasks (see Fig. 2). During all of these, participants wore headphones playing brown noise to mask noise pollution from the Haptuator. Before each task, participants completed a training session corresponding to that task, during which they experienced every stimulus in that task at least once.

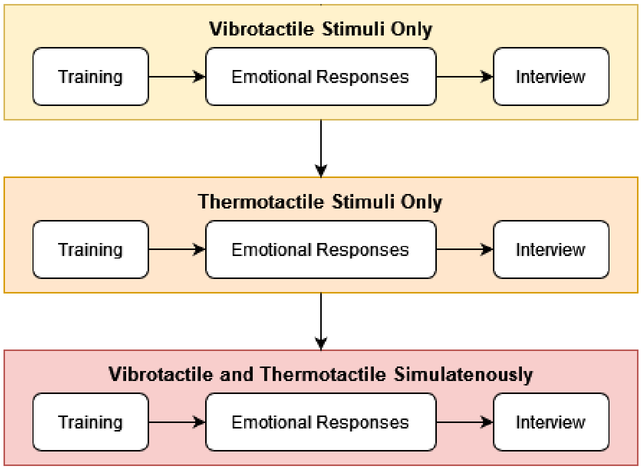

Figure 2: Diagram showing the study procedure. Participants underwent the same process in each task: a training task, followed by emotional responses to a randomised set of stimuli, followed by an interview question.

As in Macdonald *et al.*'s original study, the identity of each vibrotactile cue was given before emotional responses were recorded. The authors noted that emotionally resonant stimuli "cannot 'speak for themselves', but the affordance of labelling stimuli allows for emotional resonance" [27]. Evaluating the cues in this way is ecologically valid to any future application in which users would select their preferred stimulus before experiencing it, a recommended approach due to the individualistic responses to these stimuli found in prior studies and this study.

In Task 1, participants experienced all fifteen emotionally resonant vibrotactile stimuli and nine non-resonant stimuli presented at a neutral temperature of 30℃ in a random order until each stimulus was experienced once. After each stimulus, participants recorded their emotional response as arousal and valence on 7-point Likert scales, then reported how emotionally resonant to the given sensation they felt the haptic experience was. All Likert scale responses were encoded on a range between -3 and 3, with low responses encoded on the negative half of the scale, high responses encoded on the positive half, and neutral responses encoded as '0'. Open-ended questions were used to capture nuanced participant sentiment regarding the stimuli experienced during each task. After completing the task, participants were recorded answering the following question: *Did any specific vibrations stand out to you during the experiment and why?*

Task 2 repeated this process but participants experienced only thermotactile stimuli. In addition to the two levels later used in Task 3 (24℃ and 34℃), two intermediate levels were included, 28℃ and 32℃, to allow for more detailed observation of emotional responses to temperature, and each cue was experienced once. After completing the task, participants were recorded answering the following question: *Which temperature level did you prefer and why?*

In Task 3, participants experienced all twenty-four vibrotactile stimuli twice more, once at 24℃ and once at 34℃, in a random order.. After completing the task, participants were recorded answering the following question: *Did you think the changes in temperature affected your perception of the vibrations and why?*

3.3 Results

In order to allow two-factor parametric tests to be conducted on the Likert scale data, the Aligned Ranked Transform procedure was performed [23]. Results are reported on four topics: the affective responses to thermal stimuli presented in isolation, the affective response range of the non-resonant vibrations, the affective responses to emotionally resonant vibrations and the impact of temperature levels on the affective responses to emotionally resonant vibrations.

3.3.1 Thermotactile Stimuli in Isolation. Two one-way ANOVAs were conducted to search for a significant effect of temperature level on valence and arousal when presented in isolation. Differences in temperature had no significant effect on valence (see Table 3), but did have a significant effect on arousal (F=15.01, df=3, p<0.0001). For this, and all following ANOVAs that reported a significant result, *post hoc* pairwise testing with Tukey P-value adjustment was conducted using the *emmeans* and *artlm* R packages to search for specific contrasts between variable levels. This pairwise testing found that the coldest temperature level, 24℃, was significantly more arousing than the intermediate levels of 28℃ (effect size=1.047, p=0.0085) and 32 ℃ (effect size=1.565, p<0.0001). The warmest level, 34℃, was also more arousing than 28℃ (effect size=1.320, p=0.0085) and 32 ℃ (effect size=1.838, p<0.0001). These findings suggest that thermal cues, particularly warm cues, are more arousing the further removed they are from the neutral 30℃.

After experiencing these temperature levels in isolation, participants were asked to discuss which levels they preferred (see Table 4). Not all participants specifically preferred either warm or cold temperatures, but of those that did indicate a preference, five preferred warm, seven preferred cold, three said they disliked warm and two said they disliked cold. Six participants made comments beyond stating a temperature preference, all of which highlighted neutral or negative aspects about thermal cues. Cold stimuli were described as“sharp” or ‘almost painful”, while warm stimuli were described as feeling “alarming”, “dangerous” or “worrying”.

Temp Impact on Affect		F	Df	P.Value
Valence		0.798	3	0.500
Arousal		15.01	3	**<0.001**
Temp Arousal Contrasts	Effect Size	Estimate	T.Ratio	P.Value
24℃ - 28℃	1.047	17.55	3.311	<0.05
24℃ - 32℃	1.565	26.23	4.948	<0.001
28℃ - 34℃	-1.320	-22.12	-4.174	<0.05
32℃ - 34℃	-1.838	-30.80	-5.811	<0.001

Table 3: Table showing the results of main effect and *post hoc* testing to find the impact of temperature level on participant arousal and valence, reported on a -3 to 3 scale. Effect size given is standardised difference of means.

3.3.2 Affective Range of Non-Resonant Vibrotactile Stimuli. We hypothesised that emotionally resonant vibrotactile stimuli would prompt a wider range of emotional responses and qualitative feedback than non-resonant stimuli. The range of average valence responses to non-resonant stimuli was narrow (0.28 (*F3A3*) to 0.58 (*F1A1*)), while the range of average arousal responses was wider (0.2 (*F1A1*) to 1.92 (*F3A3*)). No non-resonant stimuli had negative arousal (see Table 2). When asked to name stimuli they found notable or preferable after Task 1, only comments were made about non-resonant stimuli, stating that they were “distinguishable”, “nice and regular”, “annoying when too long” and preferable to emotionally resonant stimuli.

3.3.3 Emotionally Resonant Vibrotactile Stimuli. Three two-factor ANOVAs were conducted to investigate the impact of the emotionally resonant stimuli and the temperature level on valence, arousal and resonance. These found that the emotionally resonant stimuli had a significant main effect on valence (F=4.418, df=14, p<0.001), arousal(F=10.98, df=14, p<0.001) and emotional resonance (F=22.98, df=14, p<0.001).

Post hoc analysis was conducted to search for significant valence contrasts between stimuli, from a possible 105 in total (see Fig. 3). Ten significant contrasts were found for valence. All but one of these contrasts featured *Cat Purring* which had a significantly higher valence (i.e was more pleasant) than nine other stimuli. The exception was a positive contrast between *Crashing Waves* and *Dog Growling*. 30 significant arousal contrasts were found. *Heartbeat* was significantly more arousing than every other stimulus in the set. *Slow Breathing* was found to be less arousing than 11 other stimuli. *Brushing* featured in seven contrasts and was significantly less arousing in each one. 44 significant emotional resonance contrasts were found. *Heartbeat* and *Cat Purring* had significantly higher emotional resonance than 12 and 11 other stimuli respectively. *Car*

Temperature	Preferred	Disliked	Comments
Warm	5	3	"Felt alarming", "Felt dangerous/worrying"x2, "More alerting"
Cold	7	2	"Almost painful", "Felt sharper", "More alerting"x2, "Numbed the hand", "Not that pleasant or arousing"

Table 4: Table summarising comments made about different temperature levels.

	F1A1	F1A2	F1A3	F2A1	F2A2	F2A3	F3A1	F3A2	F3A3
Valence	0.58	0.48	0.53	0.52	0.33	0.43	0.35	0.33	0.28
Arousal	0.20	1.07	1.62	0.67	1.12	1.45	1.00	1.22	1.92

Table 5: Mean valence and arousal responses for non-resonant stimuli, averaged across all temperature levels. F1, F2 and F3 represent 90Hz, 200Hz and 300Hz. and A1, A2 and A3 represent increasing amplitude levels calibrated dependent on frequency (See Table 2 for breakdown of frequency and amplitude levels).

Stimulus / Temperature Effect on Valence	F	Df	P.Value
Stimulus	4.418	14	**<0.001**
Temperature	10.43	2	**<0.001**
Stimulus / Temperature	1.174	28	0.245
Stimulus / Temperature Effect on Arousal	F	Df	P.Value
Stimulus	10.98	14	**<0.001**
Temperature	5.206	2	**<0.05**
Stimulus / Temperature	0.913	28	0.597
Stimulus / Temperature Effect on Resonance	F	Df	P.Value
Stimulus	22.98	14	**<0.001**
Temperature	2.889	2	0.056
Stimulus / Temperature	1.592	28	**<0.05**

Table 6: Results of three ANOVA searching for main and interaction effects of emotionally resonant stimulus and temperature level on valence, arousal and resonance.

Engine was significantly more resonant than seven other stimuli, but was less resonant than *Heartbeat*. Similarly *Underwater Bubbles* was more resonant than five stimuli but again less resonant than *Heartbeat*. *Slow Breathing*, *Dog Growling* and *Brushing* were less resonant than all or several of the stimuli previously mentioned, but all three were more resonant than *Muffled Conversation* which was the least emotionally resonant stimulus in the set and contrasted negatively with 12 other stimuli.

The mean valence, arousal and emotional resonance values for each stimulus, rated on a -3 to 3 scale, are listed in Table 7. The total ranges of affective responses to emotionally resonant stimuli were: average valence ranging from 0.03 (*Slow Breathing* / *Dog Growling* / *Scratching*) to 1.20 (*Cat Purring*) and average arousal ranging from -0.95 (*Slow Breathing*) to 1.37 (*Heartbeat*). Plotting these on a valence-arousal graph [37], nine stimuli were in the alerting and pleasant top-right quadrant and six in the bottom-right pleasant and calming quadrant (see Fig. 3).

Of the nine new stimuli added to the stimulus set which had not already featured in prior work [27], five were rated with negative emotional resonance, indicating that on average participants felt these stimuli were not resonant of the sensations they evoked. The most emotionally resonant new stimulus was *Car Engine* (0.75), making it the third most resonant stimulus in the set. Mean emotional resonance ranged from -1.48 (Muffled Conversation) to 2.23 (Heartbeat). To investigate how emotional resonance correlated with emotional response, a Pearson product-moment correlation test was conducted. A significant positive correlation was found between emotional resonance and valence (cor=0.2133, df=898 p<0.0001) and between emotional resonance and arousal (cor=0.2027, df=898, p<0.0001), suggesting that participants find stimuli they feel are more emotionally resonant, more pleasant and alerting.

	Breathing	Brushing	Bubbles	Car Engine	Cat Purr
Valence	0.03	0.30	0.50	0.61	1.20
Arousal	-0.95	-0.57	0.15	0.23	0.25
Resonance	-0.40	-0.60	0.63	0.75	1.42
	Conversation	Dog Growl	Heartbeat	Raindrops	Scratching
Valence	0.35	0.03	0.32	0.57	0.03
Arousal	0.38	0.38	1.37	0.3	0.2
Resonance	-1.48	-0.35	2.23	0.23	-0.55
	Stream	Train Tracks	Vacuum	Wave	Wind
Valence	0.65	0.42	0.37	0.75	0.33
Arousal	-0.28	0.38	-0.03	-0.12	-0.28
Resonance	0.3	0.12	-0.21	-0.10	-0.45

Table 7: Mean valence, arousal and resonance responses to emotionally resonant stimuli, averaged across temperature levels.

After experiencing all 24 vibrations at 30℃ during Task 1 participants were asked if they found any vibrotactile stimuli notable, and why (see Table 8 for results overview). *Cat Purring* and *Heartbeat* were most mentioned, described commonly as emotionally resonant and enjoyable. Four participants noted some resonant stimuli were hard to distinguish from each other. Five felt some stimuli hard to relate to unless they followed a consistent or rhythmic pattern.

3.3.4 Warm and Cold Emotionally Resonant Vibrotactile Stimuli. Three two-factor ANOVAs were conducted to investigate the effects of temperature on valence, arousal and resonance of emotionally resonant vibrations. Temperature had a significant main effect on valence (F=10.43, df=2, p<0.0001) and arousal (F=10.98, df=2, p=0.0057), along with an interaction effect with the vibration on emotional resonance (F=1.592, df=28, p<0.00271) (see Table 6).

Post hoc analysis of temperature's effect on the valence of the emotionally resonant vibrations (see Table 9) found that the cool

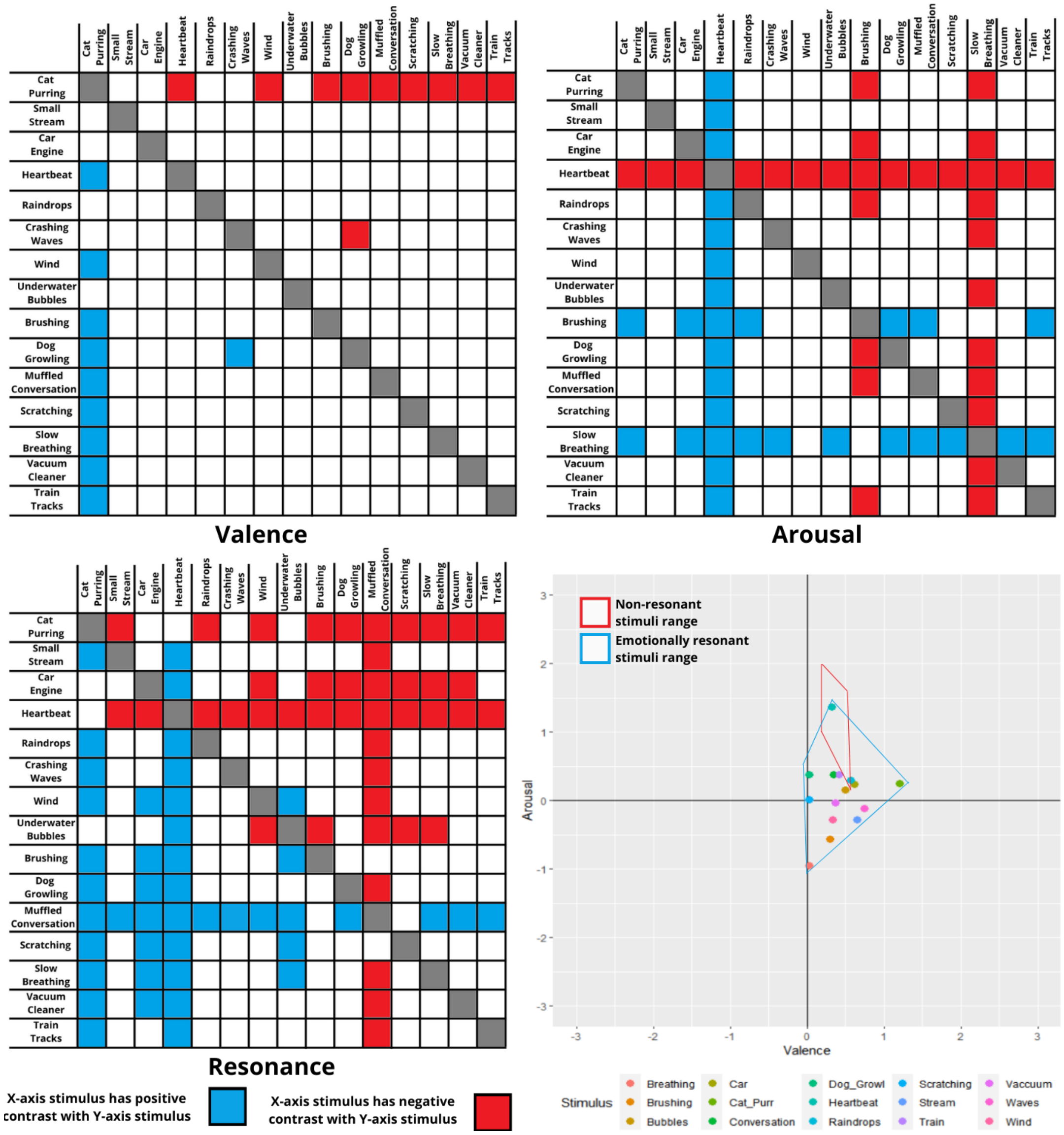

Figure 3: Figure showing three matrices displaying the significant contrasts of valence, arousal and emotional resonance between emotionally resonant stimuli and one valence-arousal plot of each stimulus' average affective response. Red squares indicate that the stimuli on the x-axis had a higher value of the associated variable than the stimuli on the y-axis, blue squares indicate the opposite. The bottom right graph shows a valence/arousal plot of the emotionally resonant stimuli, averaged across temperature levels. The blue lined area indicates the approximate affective range of emotionally resonant stimuli, the red lined area indicates the range of non-resonant stimuli not plotted to the graph (see Tab. 5)

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temperature level (24℃) prompted significantly lower valence responses than the neutral 30℃(effect size=-0.3580, p<0.0001) or warm 34℃(effect size=-0.2694, p=0.0003). Investigation of the main effect of temperature on on arousal found that emotionally resonant stimuli presented at a warm 34℃ were significantly more arousing then at a neutral 30℃(effect size=0.2620, p=0.0039). Finally, *post hoc* analysis of the interaction effect between vibration stimulus and temperature found three instances in which the temperature of a stimulus significantly changed how its emotional resonance. *Heartbeat* was less resonant at 24℃ than it was at 30℃ or 34℃ and *Small Stream* was more resonant at 24℃ than 34℃, supporting the hypothesis that emotionally resonant stimuli with expected temperatures could have their emotional resonance impacted by appropriate or dissonant thermal cues, at least in two stimuli instances.

When asked whether changes in temperature impacted their perception of vibrotactile stimuli, seventeen participants felt that

Vibration	n	Comments
Cat Purring	11	"Resonant"x2, "Enjoyable"x2, "Reminds me of my cat"
Heartbeat	9	"Resonant"x3, "Enjoyable", "Unmistakable"x2
Crashing Waves	3	"Resonant", "Water stimuli melded into one"
Dog Growling	2	"Not resonant"
Vacuum Cleaner	1	"Not resonant"
Train Tracks	2	"Made me happy"
Scratching	2	No comments
Raindrops	1	"Water stimuli melded into one"
Small Stream	2	"Felt like water"
Car Engine	1	"Reminded me of feeling the engine through the steering wheel"
Non-Resonant Stimuli	4	"Annoying when too long", "Preferred Abstract Stimuli", "Nice and Regular", "Distinguishable"

Table 8: Table summarising how often participants stated that certain stimuli stood out to them, where n = number of total times mentioned, and what specific comments were made about each stimulus during Task 1 interviews.

Temperature Valence Contrasts	Effect Size	Estimate	T.Ratio	P.Value
24℃ - 30℃	-0.3580	-86.7	-4.385	<0.001
24℃ - 34℃	-0.2694	-65.2	-3.299	<0.05
Temperature Arousal Contrasts	Effect Size	Estimate	T.Ratio	P.Value
30℃ - 34℃	-0.262	-59.7	-3.926	<0.05
Stimulus / Temp Resonance Cons.	Effect Size	Estimate	T.Ratio	P.Value
Heartbeat 24℃ - 30℃	-1.2414	-13.45	-3.926	<0.001
Heartbeat 24℃ - 34℃	-1.3198	-14.30	-4.174	<0.001
Small Stream 24℃ - 34℃	1.1680	11.28	3.692	<0.05

Table 9: Table showing the significant pairwise contrasts between different temperature levels on valence and arousal, and the interaction effect between stimuli and temperature on emotional resonance, all measured on a -3 to 3 scale. Interaction effect was investigated specifically to find if any stimuli changed in emotional resonance when the temperature level changed and an alpha of 0.0033 was set with Bonferroni Correction to account for each of these potential contrasts.

temperature made a significant difference to their general perception, while three felt that temperature made little or no difference. However, only three significant interactions on emotional resonance were found between stimuli presented at different temperature levels during *post hoc* analysis. This could suggest that the hypothesised effect of temperature on emotional resonance is more common than quantitative testing indicated, but varies between individuals too strongly to produce a strong statistical effect.

Seven comments stated that warm temperatures made the *Heartbeat* and *Car Engine* stimuli more resonant. Four comments stated that stimuli which evoked water sensations were more resonant when cold. Six participants stated that cold cues made various stimuli more dissonant, including *Heartbeat*, *Cat Purring*, *Slow Breathing* and *Car Engine*, while warmth made them more resonant. Four participants felt that water stimuli like *Small Stream* and *Underwater Bubbles* could be resonant at either temperature, but it changed their meaning from "cold and refreshing" to "boiling". Five participants felt that dissonant temperatures made stimuli harder to identify and six participants felt temperature had an effect on stimuli pleasantness, but did not specify further. Only stimuli which were hypothesised to have an 'expected' temperature 1 were mentioned by participants during qualitative feedback .

4 DISCUSSION

4.1 Emotional Response and Resonance Ratings of a Larger Emotionally Resonant Vibrotactile Stimuli Set

This study followed early emotionally resonant vibrotactile studies [27, 44], but measured emotional responses to a larger set of stimuli and recorded emotional resonance ratings after each presentation. The range of affective responses to the stimuli previously used by Macdonald *et al.* was similar, corroborating the results of this earlier work. The majority of stimuli added in this study received neutral affective ratings and neutral or negative resonance ratings. The stimuli with the most notable affective ratings and highest quantity of qualitative comments were *Cat Purring* and *Heartbeat*, both drawn from the original set. Emotionally resonant stimuli elicited a wider affective range of mean valence and arousal values than non-resonant stimuli, and seven emotionally resonant stimuli exceeded the non-resonant stimuli ranges for both valence and arousal respectively. Notably, four emotionally resonant stimuli had valence ratings above the maximum range of non-resonant stimuli and seven had arousal ratings below the non-resonant range, putting these cues in desirable areas on the Circumplex Model for producing calming and pleasant stimuli.

Affective responses to some emotionally resonant stimuli significantly contrasted to others in the set, indicating these stimuli are likely to elicit more consistent responses across a population. *Cat Purring* was responsible for all but one of the significant valence contrasts, highlighting its potential for use in creating pleasant haptic experiences. *Heartbeat* was significantly more arousing than every other stimuli, and significantly more emotionally resonant than all stimuli except *Cat Purring*. *Slow Breathing* and *Brushing* were significantly less arousing than many other stimuli, making them potentially useful for creating calming haptic experiences. *Cat Purring*, *Heartbeat*, *Car Engine* and *Underwater Bubbles* were rated as significantly more emotionally resonant than at least five other stimuli by participants. Emotional resonance is desirable trait; such stimuli can impart more meaning than generic vibrations and are positively correlated with arousal and valence. It can also evoke specific memories, experiences and their related emotions, and could reinforce media presentation by evoking sensations that match those currently being conveyed by other modalities.

While this study found that some emotionally resonant stimuli exceeded the affective range of non-resonant vibrations, it is not unexpected for some emotionally resonant stimuli to exhibit neutral affective responses across a participant set. As noted in prior work [27], affective responses to emotionally resonant stimuli rely on whether each individual can reconcile the stimulus presented with personal experience and their subsequent associated emotions, making consistent performance across users unlikely. While stimuli like *Cat Purring* and *Heartbeat* were effective for more participants, other stimuli like *Train Tracks*, *Crashing Waves*, *Raindrops* and *Scratching* were still highlighted as personal preferences by some. Thus, while it is valuable to identify which stimuli are most effective for the widest audience, it is recommended when utilising this category of vibrotactile stimuli that users are allowed to select a preferred stimulus from a varied set, increasing the likelihood of finding at least one sensation they find resonant, emotionally preferable and suited to their experiences. It would be beneficial for future work to test this personalised approach and observe if it results in a meaningful affective interface for each participant.

4.2 Impact of Thermal Cues on Emotionally Resonant Vibrations

Our findings supported the hypothesis that thermal cues would have a significant positive effect on valence and arousal when presented alongside emotionally resonant vibrations. Stimuli were more pleasant at neutral (30℃) and warm (34℃) temperature levels than cold (24℃) and the warm level was also more alerting than the neutral. While this suggests that the addition of warm thermal cues could be valuable in creating more noticeable and pleasant emotionally resonant stimuli, the effect sizes on both valence and arousal were small. Thermal actuators, like the Peltier, are generally larger and less easy to integrate into interfaces than vibration actuators and require users to touch specific thermal elements. Vibration actuators are already built into the many smart and wearable devices and vibration can radiate throughout the device, requiring less specific interaction from users. Future haptic designers must choose if the affective benefits of thermal cues are worth the potential trade-off in interface size and practicality.

When considering the impact of temperature on emotional resonance, it was hypothesised that stimuli which evoked a real-world sensation with an 'expected' temperature, such as warmth and *Cat Purring*, or cold and *Small Stream*, would become more resonant when presented alongside that temperature and *vice versa*. Quantitative analysis found this effect occurred for two of the eight stimuli with expected temperatures: *Heartbeat* was significantly more resonant at neutral and warm temperature levels than it was at a cold level. *Small Stream* was significantly more resonant when presented alongside a cold temperature than a warm one, and the size of these effects were over four times larger than the effects of temperature on emotional response. Qualitative comments made by 17 participants stated they felt resonance changed due to temperature, for total of six of the eight expected temperature stimuli, including *Slow Breathing*, *Car Engine* and *Cat Purring*. It is clear that the hypothesised effect can occur, but does not occur uniformly between participants. This is unsurprising, as responses to emotional resonant stimuli are highly individual, depending on if the user can associate the stimuli with their personal experiences and what their emotional association with the experiences is [27]. *Heartbeat*, for example, was the most resonant stimuli, had a clear associated temperature and is a constant human experience, contributing to it temperature having a strong statistical effect on its resonance.

Given these findings, thermotactile stimuli have utility in crafting more immersive and emotionally resonant haptic experiences, but in most cases not consistently between users. As emotional resonance allows vibrotactile stimuli to elicit a wider range of emotional responses, particularly in regards to valence, this could further enhance this ability. We posit that, if future interfaces provide users with a range of emotionally resonant stimuli and temperatures to choose from, allowing them to pick a multimodal combination they prefer and find most resonant, the individualistic nature of responses to emotionally resonant stimuli can become a strength, allowing users to develop a positive personal relationship with the interface and elicit a positive emotional response as a result. Affective haptics has already shown the ability to promote calming, pleasant emotion regulation [26, 48, 58], and the ability for emotionally resonant stimuli to evoke meaningful emotional responses could further enhance this effect. Evoking real-world sensations also allows these stimuli to be utilised in immersive multimodal media experiences [16, 25], and the flexibility of single actuator vibrations allows them to be housed into pre-existing interfaces like chairs, mobile devices or game controllers.

4.3 Limitations and Future Work

The ordered structure of tasks used, as opposed to counterbalancing, could make the results vulnerable to presentation bias. This structure was chosen to allow participants to give qualitative feedback regarding bimodal stimuli with the context of having experienced all unimodal stimuli previously, better informing their ability to compare modalities. Given disparate preferences for temperature level it could be valuable to study how an individual's preference impacts their experience with bimodal stimuli, particularly when their preferred temperature is dissonant with the emotional resonance of the vibrotactile cue. Given a relatively small sample size and the individualistic natures of responses, it is hard to draw widespread conclusions from this study, but this early insights do serve to highlight the meaningful affective responses possible when combining emotionally resonant vibrations and thermal cues.

5 CONCLUSION

This paper presents an exploration of a large set of emotionally resonant vibrotactile cues and novel observations of how thermotactile cues can impact emotional responses and resonance. The affective range of emotionally resonant stimuli exceeded that of non-resonant stimuli, particularly achieving higher valence and lower arousal, and going beyond the range found in existing research. Specific stimuli like *Cat Purring*, *Heartbeat*, *Slow Breathing* and *Car Engine* had significantly contrasting valence, arousal or emotional resonance ratings when compared to the set, supporting their applicability to a wider proportion of users. Warm thermal cues had a small but significant positive effect on the valence and arousal of emotionally resonant vibrations, and the resonance of two stimuli was significantly altered when presented at appropriate or dissonant temperatures, suggesting that adding thermal cues can further widen the range of haptic experiences. This research contributes a better understanding of a wider range of emotionally resonant vibrations, how they interact with thermal cues, and highlights their potential to improve affective haptic applications such as emotion regulation and immersive multimodal media.

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