Eliciting Emotion with Vibrotactile Stimuli Evocative of Real-World Sensations

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Figure 1: Emotionally resonant stimuli evoke real-world sensations. A user's emotional response to a stimulus may be similar to their emotional response to the original real-life sensation it evokes.

ABSTRACT

This paper describes a novel category of affective vibrotactile stimuli which evoke real-world sensations and details a study into emotional responses to them. The affective properties of short and abstract vibrotactile waveforms have previously been studied and shown to have a narrow emotional range. By contrast this paper investigated emotional responses to longer waveforms and to *emotionally resonant vibrotactile stimuli*, stimuli which are evocative of real-world sensations such as animal purring or running water. Two studies were conducted. The first recorded emotional responses to Tactons with a duration of 20 seconds. The second investigated emotional responses to novel emotionally resonant stimuli. Stimuli that users found more emotionally resonant were more pleasant, particularly if they had prior emotional connections to the sensation represented. Results suggest that future designers could use emotional resonance to expand the affective response range of vibrotactile cues by utilising stimuli with which users bear an emotional association.

CCS CONCEPTS

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

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KEYWORDS

Vibrotactile; Affective Touch; Emotional Resonance

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1 INTRODUCTION

Understanding how to elicit emotion from touch interaction would give interface designers the tools to enable new and enhanced experiences. Emotional touch could allow for novel emotional interactions when a user's vision, voice or hearing are occupied in environments such as conversation, films or social spaces. The variety of possible interactions is, however, hampered by the narrow affective range of vibrotactile stimuli [13, 33, 38], especially along the valence (pleasantness) axis of Russell's Model of Affect (see Fig. 2) [24]. Vibrotactile stimuli have been most effective at communicating and evoking urgency [33], a common application in the form of notification alerts. This narrow emotional range could be expanded by utilising evocative 'emotionally resonant' vibrotactile stimuli, which we define as stimuli that evoke a specific real-world sensation (e.g. waves crashing, cat purring) and thus elicit the associated emotions the user feels regarding that sensation.

Previous research regarding affective, or emotional, vibrotactile touch has focused primarily on short abstract waveforms [13] or Tactons [5, 38]. Vibrotactile stimuli that evoke real-world sensations have been used alongside other sensory elements to generate emotional responses in fields like social robotics, where Yohanan's *Haptic Creature* simulated animal purring [36]. There is, however, a lack of research on the affective properties of such stimuli when experienced without other modalities. Vibrotactile actuators are already integrated into devices like smartphones and increasing their affective capabilities could allow for a broader range of emotional experiences for users. Can vibrotactile stimuli be emotionally resonant when experienced in isolation and do they have different affective properties than abstract stimuli such as Tactons?

Emotional resonance has been used in modalities like sound to elicit emotions. Several studies found that sounds or music that remind participants of pleasant and calming memories elicited associated calm and relaxed emotions [4, 7, 12, 29]. Czech *et al.*'s *Haptic Remembrance Book* [8] and social robots like *Paro the Seal* [32] have used a resonant combination of sound, visual and haptic cues to evoke positive emotional responses. What has yet to be established is whether vibrotactile cues can evoke similar emotional responses in isolation and which sensations are most emotionally resonant in this context.

This paper presents two initial studies. The first investigated the effects of increased duration on previously examined vibrotactile stimuli. In order to evoke real-world sensations with complex waveforms, significantly longer stimuli may be needed, but there is no clear picture on how this duration increase changes emotional response. Therefore, the first experiment is designed to assess how significantly longer stimuli affect emotional response. The second study assessed whether emotionally resonant vibrotactile stimuli could be designed to evoke a wider range of affective responses than previously studied cues and which sensations are more emotionally resonant. In both studies, participants self-reported affective responses to different stimuli in terms of valence and arousal using Likert scales, as well as giving qualitative feedback.

1.1 Contribution Statement

We make the following contributions in this paper:

- First experimental measurement of the affective responses of Tactons 20 seconds in length;
- Observation of affective responses to a variety of novel emotionally resonant vibrotactile stimuli;
- Identification of which sensations were most emotionally resonant when conveyed only using vibrotactile feedback;
- Discussion of how the recognition and emotional resonance of stimuli affected their emotional properties.

2 RELATED RESEARCH

2.1 Modelling Emotion

The prominent model for measuring emotion in affective touch research is Russell's Circumplex Model of Affect [24]. This is a two-dimensional model of valence (unpleasant-pleasant) on the x-axis and arousal (sleepiness-alertness) on the y-axis, with each scale's neutral value intersecting (see Fig. 2). This creates a plot with four quadrants: pleasant and alerting, unpleasant and alerting, pleasant and calm, and unpleasant and calm emotions. Russell mapped 28 recognisable emotions around this plot.

This model has been widely used in previous affective touch studies, e.g. [10, 11, 13, 33, 38]. A participant's subjective arousal and valence responses can be approximated to more specific emotions or emotional states based on the quadrants defined by Russell's

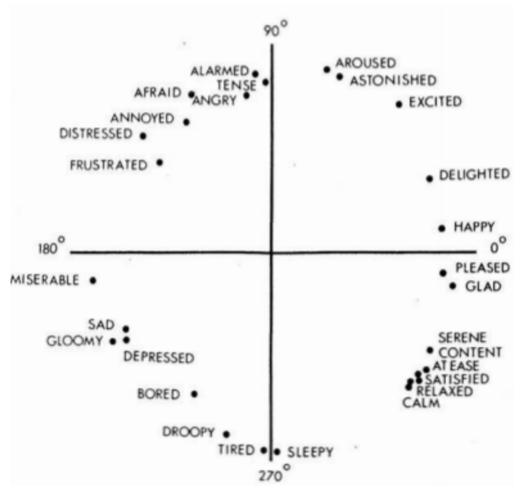


Figure 2: Russell's Circumplex Model of Emotion [24]. The y-axis represented arousal or alertness, while the x-axis represents valence or pleasantness. Russell mapped 28 different affect terms around this circular model to demonstrate how these two scales represent specific emotions.

model. Using this model also allows for better external comparisons with other affective studies.

2.2 Vibrotactile Affective Touch

Human perception limits must be considered when working with vibrotactile stimuli. While humans can perceive stimuli to some extent in a 10-500Hz frequency range [6, 20, 31], van Erp's guidelines highlight that the greatest sensitivity is between 200-250Hz, on glabrous skin and as stimuli duration increases [31].

Contemporary study of the emotional properties of vibrotactile stimuli began with Seifi *et al.*'s 2013 investigation of affective responses to vibration [26]. This study used 1 second stimuli, with 2 frequency levels and 6 different rhythms. They identified that stimuli were 'mostly perceived as rough, alarming and unpleasant; or, smooth, calm and pleasant'. Additionally, frequency had a significantly positive effect on arousal.

Yoo *et al.* [38] presented a study measuring the effects of 4 parameters: duration, amplitude, frequency and envelope, on affective responses to vibrotactile icons, or 'Tactons' [5]. Summarising their findings; amplitude and duration had a positive effect on arousal, envelope frequency had a negative effect on valence, and Tactons with higher amplitude or arousal levels tended to causes a wider range of valence levels.

Hasegawa *et al.* [13] reported affective responses (arousal, dominance, comfort, preference and familiarity) to vibrotactile stimuli varied by amplitude, rhythm, duration, envelope frequency and waveform. Their results affirmed Yoo *et al.*'s findings on the effects of amplitude, but diverged on envelope frequency, showing positive effects on preference and comfort.

Other research has examined affective responses to multimodal stimuli, including responses to vibrotactile stimuli in isolation. Akshita *et al.* [1] found that amplitude positively influenced arousal and negatively influenced valence, while frequency had no effect on arousal but a positive effect on valence. Wilson *et al.* [33] performed a near-replication of Yoo *et al.*'s study [38]. They shared some similar findings: an inverse relationship between arousal and valence, and amplitude, frequency and duration having positive effects on arousal, but also diverged, reporting that frequency had a positive effect on valence. When combined with another modality, vibrotactile cues primarily influenced the arousal of the overall sensation. This held true in a study by Salminen *et al.*, in which vibration was presented alongside speech samples with amplitude modulation matching the speech [25], making speech samples less pleasant but more arousing.

Emotional touch can also result from the stimulation of CT afferents, found in non-glabrous skin. These receptors respond to slow stroking sensations, triggering a pleasant sensation [19, 21]. The requirement for a brushing motion can, however, make CT afferents impractical to utilise.

These studies show that while some of the affective properties of vibrotactile stimuli are known, such as the effect of amplitude and the relationship between arousal and valence, other effects are inconsistent. All these studies used stimuli between 0.1 and 2 seconds in length, and while they varied waveforms and rhythms, the stimuli were all simple abstract sensations.

2.3 Emotional Resonance

The emotional resonance of modalities such as sound has proved effective in prior research. Several studies have shown that sounds that patients find relaxing or calming can reduce pain or stress during surgery [2, 7, 29]. Both Tsuchiya *et al.* [29] and Arai *et al.* [2] utilised natural sounds (e.g. forest breezes, streams), chosen by participants, to successfully reduce pain and stress during surgical procedures. Cutshall *et al.* [7] allowed patients to choose an ambient therapy CD that combined relaxing nature sounds with an algorithmically generated musical accompaniment to promote relaxation. They hypothesised doing so would "provide patients with a new perceptual reality so that the hospital environment is soothing and comforting". Patients in the treatment group experienced significantly lower pain and anxiety.

Emotionally resonant sound has been used in other contexts to elicit similar positive emotions. In two studies seeking to simulate natural environments, Ogden *et al.* [23] and Valtchanov *et al.* [30] included ambient natural noise. Both found the environments created were calming for participants, and Ogden *et al.* reported that emotional responses were significantly more positive compared to a sound-free control condition. In a study investigating the efficacy of Bedside Sound Generation as a sleeping aid for patients with tinnitus, Handscomb *et al.* [12] suggested the emotional resonance of a sound played an important role. Sounds like a heartbeat elicited negative emotions due to prior emotional association ("the heart beat reminds me of horror films"). In a study examining soundscape preferences in an urban square, Yang *et al.* [34] found that quiet natural sounds were most relaxing and pleasant. Participants made an emotional connection between these natural sounds and the ability to "escape from usual busy life" in a city environment.

Others have utilised vibrotactile sensations as part of emotionally resonant experiences, alongside other modalities such as visuals and sound. Czech *et al.*'s 'Haptic Remembrance Book' for care home residents [8] used pages with touch and audio displays that presented sensations reminiscent of the user's past experiences to spur enjoyment and conversation about old memories.

Robots like Paro the Seal and The Haptic Creature [36] exhibit animal-like sound and movement. Paro [32] was developed for use in care homes where the majority of residents formed positive emotional relationships with it, using it as a catalyst to form closer relationships [32]. Yohanan's Haptic Creature [36] expressed specific emotional states through various small movements, including vibrotactile purring. Those interacting with The Haptic Creature felt lower arousal and higher valence [35]. Animal therapy can have relaxing effects [3] and it has been suggested social robots which are resonant of pets could impart similar benefits [37].

This body of research suggests there is potential to evoke emotion using emotionally resonant sensations. Additionally, vibrotactile stimuli have been combined with other modalities to create emotionally resonant experiences. There is, however, no strong indication of how evocative vibrotactile stimuli could be in isolation, or how well previously proven emotionally resonant sensations like sound can be displayed using vibration.

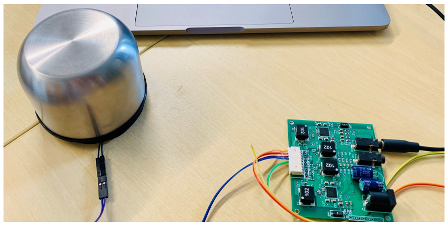
3 EXPERIMENTAL APPARATUS

The following apparatus was used to conduct both studies, with minor changes made to the user interface for Study 2 to facilitate the recognition of different emotionally resonant stimuli. Vibrotactile stimuli were presented using a Haptuator Mark II, which can present 98% of haptic bandwidth (10Hz-7kHz) [17]. This was chosen to allow for external validity with Wilson *et al.*'s most recent affective vibrotactile research [33], which used the same device. The Haptuator was mounted to the inside of a flask cap, which presented a large rounded surface that could fill the hand of a participant, while being rigid enough to convey vibration effectively (see Fig. 3). The flask cap was filled with soft foam to mask noise.

To ensure no sounds from the actuator were perceived, participants wore headphones playing brown noise. Vibrations were delivered to the Haptuator and flask cap using a 3.5mm cable and amplifier by a MacBook Pro, with its volume level set to 6. Participants sat at a desk and rested the flat of their palm on the circular top of the flask cap with their fingers resting down the sides. The entire cap was vibrated by the Haptuator and so the stimuli were presented to the majority of the palmar side of the hand. The flask cap was oriented so that the internal Haptuator was positioned perpendicularly to the edge of the desk to prevent intensity being altered by changing orientation [16, 33]. Participants self-reported valence and arousal on the laptop, as well as stimuli recognition. Audacity was used when designing the emotionally resonant stimuli used in Study 2.

4 STUDY 1: AFFECTIVE PROPERTIES OF DURATION ON VIBROTACTILE STIMULI

The primary aim of this study was to establish how significantly increasing the duration of a Tacton from 2 seconds to 20 seconds changed participants' affective response to it. We hypothesised that, while in previous studies a duration of 5 seconds led to increased arousal, significantly longer 20 second stimuli would lead to overall



(a) The Haptuator handrest, amplifer and laptop.

(b) Hand positioned on the Haptuator handrest.

Figure 3: Experimental apparatus used in this paper. A Haptuator Mark II was mounted inside the metal flask cap. It was connected to a laptop via an amplifier. Participants were asked to rest their hand filled by the Haptuator flask cap.

lower arousal as participants acclimatised to the sensation and the physical effects of habituation took effect.

4.1 Experiment Design

4.1.1 Stimuli. To increase external validity, the Tactons had identical values of amplitude and frequency in a sinusoidal waveform to those used by Wilson *et al.* and Yoo *et al.*, along with the same envelope function which was detailed by Yoo *et al.* [38]. We used 2 duration levels of 2 seconds and 20 seconds. Wilson *et al.*'s amplitude levels, measured by gravitational acceleration, were subjectively scaled to feel similar across 3 frequency levels.

18 stimuli were used, varied across 3 independent variables: amplitude, frequency and duration (see Table 1). Participant responses were recorded across 2 dependent variables: valence and arousal.

This study used a similar procedure to previous affective touch studies [13, 26, 33, 38]. We displayed each stimulus once for each affective reading, as opposed to repeating them 3 times in quick succession, to keep the same procedure across both short and long stimuli. In order to observe how participant qualitative feedback changed over as long a duration as possible, pilot tests were performed to find the maximum acceptable duration. 20 seconds was chosen as pilot participants consistently reported longer stimuli as frustrating or boring to experience in the context of the experiment.

4.1.2 Experimental Procedure. This study had 20 participants (10M, 10F) recruited from the University campus and mailing lists. Each experiment, comprised of two tasks, took around 20 minutes. During the first task, all 2 second stimuli were presented twice in a random order. In the second task all 20 second stimuli were presented.

Parameter	**Values**			**A1**	**A2**	**A3**
Amplitude	A1,A2,A3		*90Hz*	1.7g	3.3g	4.3g
Frequency (Hz)	90,200,300		*200Hz*	0.6g	1.0g	1.3g
Duration (s)	2,20		*300Hz*	0.9g	1.2g	2.2g

Table 1: Independent Variable levels used to generate 18 different stimuli in Study 1 (g = gravitational acceleration).

Splitting duration levels between two tasks allowed participants to more easily contrast them during qualitative analysis. After each stimulus, participants reported arousal and valence on a 7 point Likert scale, converted to a +3 to -3 range. In an open-ended interview, after both tasks were completed, participants were asked 3 questions regarding how they perceived different stimuli and how this affected their emotional responses. They were asked which vibrations they found most alerting and which most pleasant. They were then asked if they noticed a difference in their perception of the longer and shorter vibrations. Finally, they were given the opportunity to make comments or ask questions.

4.2 Results

To analyse the non-parametric within-subjects Likert data we applied the Aligned Rank Transform [18], allowing for traditional parametric testing. Four two-factor mixed-effects ANOVAs were run to search for effects between duration and frequency or amplitude on valence and arousal. Two further ANOVAs searched for effects between frequency and amplitude on valence and arousal, to allow for external comparisons with previous studies [13, 33, 38].

	Amplitude			**Frequency (Hz)**			**Duration (s)**	
	A1	**A2**	**A3**	**90**	**200**	**300**	**2**	**20**
Valence	0.66	0.54	0.03	0.37	0.62	0.24	0.42	0.39
Arousal	-0.70	0.10	0.87	0.88	-0.35	-0.26	0.00	0.18

Table 2: Mean valence and arousal (-3 to 3) for each in dependent variable level in Study 1.

We found no main effect of duration on arousal or valence. We did find an interaction effect between duration and frequency ($F=3.06$, $p<0.05$) and so performed interaction analysis with a Holm-Bonferroni correction [15] using the R phia package [14]. This test revealed a significant difference between frequencies of 90Hz and 200Hz at 2 and 20 seconds which can be seen in Fig. 4.

We found a significant main effect of amplitude on both arousal ($F = 63.43$, $p < 0.001$) and valence ($F = 10.85$, $p < 0.001$). Frequency had a main effect on arousal ($F = 46.81$, $p < 0.001$) but none on valence. Previous work [13, 33, 38] found a mixture of positive and negative effects on valence by frequency. Increasing amplitude correlated with increasing arousal and decreasing valence, which echoed previous findings [13, 33, 38], while increasing frequency correlated with decreasing arousal, supporting findings by Hasegawa *et al.* but contradicted by Wilson *et al.* [33] and Yoo *et al.* [38].

4.2.1 Qualitative Feedback. Qualitative feedback both corroborated and diverged from the quantitative data. The most common theme concerned arousal, mentioned by 12 participants, echoed the data that stronger, higher amplitude stimuli were more alerting. 11

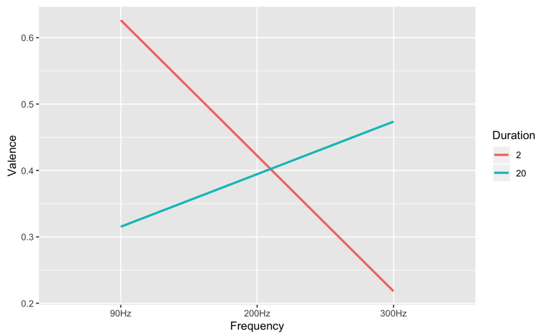
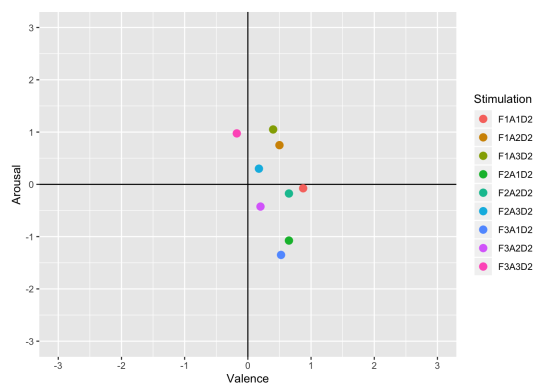
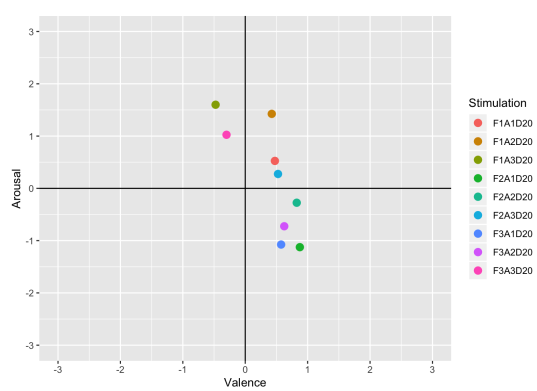


Figure 4: Interaction plot showing the average valence for 2 and 20 second stimuli for each level of frequency. Participants felt that 2 second cues were significantly more pleasant than 20 cues at 90Hz, but felt the opposite at 300Hz.



(a) Emotional Responses to 2 Second Stimuli



(b) Emotional Responses to 20 Second Stimuli

Figure 5: Emotional responses expressed in mean valence and arousal to 20 second stimuli produced by varying frequency and amplitude (see Table 2).

participants felt higher frequencies were more alerting, while 8 felt the opposite. This contrasted findings from the data that frequency had a negative effect on arousal, suggesting participant perception of these stimuli wasn't universal. Some participants felt that certain frequencies 'felt almost like a massage' during longer stimuli, but there was no consensus on which frequency caused this effect.

The perceived effects of increased duration were varied and no single effect was mentioned by more than 7 participants. The most common sentiments were: (1) The extra time allowed for better understanding of the stimuli (6 participants), (2) After 8-12 seconds hand sensation lessened or deadened (7 participants); (3) Waiting 20 seconds to rate a stimulus became annoying (4 participants); and (4) Longer stimuli were more pleasant (5 participants). This suggests there is value to extending the duration of stimuli beyond the 1,2 and 5 seconds of previous studies, but 20 seconds may be too long. Habituation effects, a likely cause of the sensation deadening experienced, could impede the ability for participants to perceive stimuli. Additionally, in the context of an experiment rating 18 stimuli sequentially, waiting for stimuli to finish after already comprehending them could be frustrating. In future using a duration shorter than 20 seconds may allow the aforementioned benefits, such as better stimuli comprehension and increased pleasantness, while mitigating the disadvantages participants outlined. This finding informed the decision to set the stimuli duration of the following study to 10 seconds.

5 STUDY 2: EMOTIONALLY RESONANT VIBROTACTILE STIMULI

This study's primary goal was to assess the affective properties of emotionally resonant vibrotactile stimuli. We hypothesised that participants would find stimuli emotionally resonant if they felt an emotional connection to the sensation being evoked and either recognised the stimuli or were given its identity. We further expected that more emotionally resonant stimuli would achieve a wider valence range than previous affective vibrotactile research, with the pleasantness of the stimuli depending on each participant's emotional association with that sensation.

5.1 Experiment Design

This experiment featured two tasks performed by each participant. During Task 1, participants attempted to identify the stimuli presented. In Task 2, participants were given the identity of the stimuli. In both cases, they rated them in terms of valence and arousal. These tasks were designed to observe the affective responses to emotionally resonant stimuli, see if each stimulus was recognisable on its own, and whether knowledge of a stimulus's identity effected emotional responses to it. Labelling stimuli in Task 2 also allowed observation of how participants would respond when they have knowledge of the stimuli they experienced, as they would using a real world customisable application. We hypothesised that participants would form emotional associations with vibrotactile stimuli they found resonant, would have a wider range of valence responses to stimuli they found more resonant, and that participants would find stimuli more resonant when they knew what they represented. This experiment featured 1 independent variable for both tasks: the stimulus set. Both tasks featured valence and arousal as dependent variables and Task 1 also measured how accurately participants could identify different stimuli without training.

5.1.1 Stimuli. In total, a set of 8 stimuli were used: a heartbeat, cat purring, human breathing, bubbling water, waves crashing, leaves rustling, a babbling brook and muffled conversation. The first 4 were chosen as they are sensations with both audio and haptics modalities found in the real world. The rest were chosen as they were shown as emotionally evocative in previous studies which used emotional sound [2, 7, 30, 34]. The heartbeat had a relaxed heart rate of 60 beats per minute and breathing was recorded at a relaxed rate of 12 breaths per minute. We generated the stimuli from sound recordings as artificial patterns would require significant iteration until they could be proven to be representative of the intended sensation.

All raw sound files were sourced from Freesound [28]. The volume levels of these files were then normalised to 89dB, a volume high enough to display the stimuli effectively, using the tool Mp3Gain [22]. As discussed in Section 2.2, human vibrotactile sensitivity is highest in the 200-250Hz range and functional between 10 and 500Hz. The stimuli used in this study, being recordings of natural phenomena, fit only partially into this range. Vibrotactile stimuli produced from complex audio stimuli cannot be perceived at the same level of detail and frequency range, but this study aimed to assess whether this limited perception can still be resonant for users, with or without prompts.

Stimuli were pilot tested for clarity and some had bass frequencies amplified (0Hz-100Hz) using Audacity [27]. The sound files for human breathing, babbling brook, crashing waves and heavy rain were amplified by 15 dB, while leaves rustling and muffled conversation were amplified by 30 dB.

Stimuli were either looped or cropped to a duration of 10 seconds. This duration allowed time to comprehend the sensation being conveyed, while being shorter than the stimuli used in Study 1 to reduce habituation and boredom effects.

5.1.2 Experimental Procedure. 20 participants (9M, 8F, 3 Non-Binary) took part and in total both tasks took 40 minutes. In each task, participants experienced each stimulus 3 times in a randomised order, then reported arousal and valence on 7-point Likert scales, converted to a +3 to -3 range. During Task 1, participants were asked to choose what sensation each stimulus reminded them of from a selection of options included all the stimuli presented and other real-world sounds (see Fig. 6). During Task 2, the identify of each stimulus was presented along with the Likert scales.

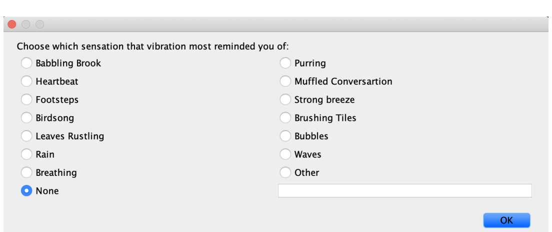
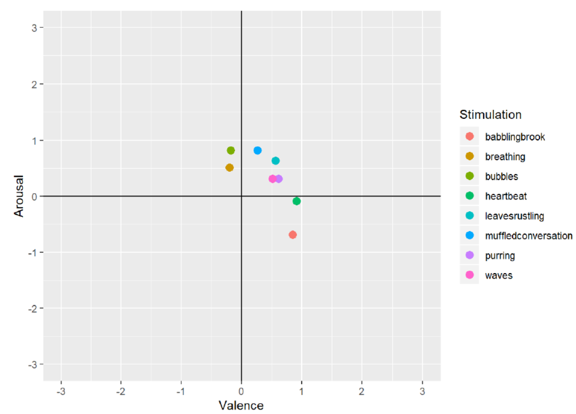


Figure 6: Panel displayed to participants during Study 2 - Task 1 after they have submitted valence and arousal ratings for a stimulus. Participants had to say which of the following given sensations that stimulus reminded them of, if any.

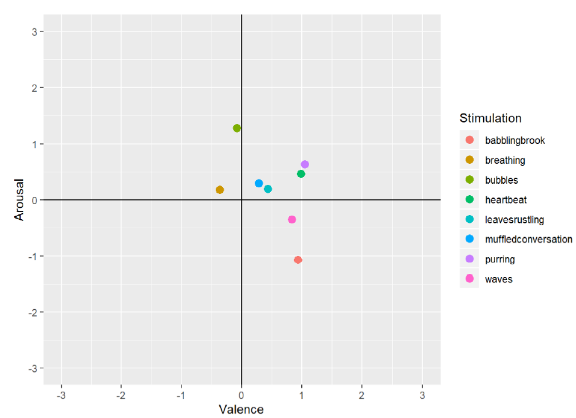
Once both tasks were finished, participants took part in a short open-ended interview. They were asked if they noticed a difference in their perception between the two tasks, if any stimulus felt more or less resonant once their identity was given, and if any stimuli stood out to them for any reason.

5.2 Results

After performing an Aligned Ranked Transform on the Likert scale data, a series of 5 ANOVAs were run to examine if different stimuli received different valence and arousal ratings in Task 1, then again in Task 2, and if different stimuli were recognised with different levels of accuracy. This stimulus set had a significant main effect on valence in Task 1 ($F = 4.09$, $p < 0.001$); arousal in Task 1 ($F = 6.08$, $p < 0.001$); accuracy in Task 1 ($F = 20.4$, $p < 0.001$); valence in Task 2 ($F = 5.20$, $p < 0.001$); and arousal in Task 2 ($F = 9.88$, $p < 0.001$). As each ANOVA found a significant main effect, each was followed with *post hoc* pairwise testing to determine which specific stimuli were responsible for the effect, utilising the emmeans R library and tukey P value correction.



(a) Emotional Responses to Task 1 Emotionally Resonant Stimuli



(b) Emotional Responses to Task 2 Emotionally Resonant Stimuli

Figure 7: Emotional responses on a mean valance and arousal graph to 8 stimuli generated from real-world sensations in Task 1 and Task 2.

	Task 1			Task 2	
	Mean Valence	**Mean Arousal**	**Mean Accuracy**	**Mean Valence**	**Mean Arousal**
Babbling Brook	0.85	-0.683	10%	0.933	-1.07
Breathing	-0.2	0.517	5%	-0.367	0.183
Bubbles	-0.183	0.817	15%	-0.0833	1.28
Heartbeat	0.917	-0.083	93.3%	0.983	0.467
Leaves Rustling	0.567	0.633	6.67%	0.433	0.2
Muffled Conversation	0.267	0.817	10%	0.283	0.3
Purring	0.617	0.317	26.7%	1.05	0.633
Crashing Waves	0.517	0.317	15%	0.833	-0.35

Table 3: Study 2: Mean valence, arousal and accuracy for each stimulus in Task 1 and mean valence and arousal in Task 2.

Task 1: Stimuli Effect on Valence, Arousal and Accuracy
4 stimuli had significantly divergent valence responses from each other during Task 1: Babbling Brook, Breathing, Heartbeat and Bubbles. Babbling Brook (see Table 3) and Heartbeat were both significantly more pleasant ($p < 0.05$) when compared to both Slow Breathing and Bubbles.

In Task 1 Babbling Brook (see Table 3) was less arousing than every other stimulus except Heartbeat. Heartbeat was significantly less arousing ($p < 0.05$) than Bubbles and Muffled Conversation.

Heartbeat (see Table 3) was the most accurately identified stimulus ($p<.0001$), strongly contrasted with every other stimuli. Purring was the second most accurately identified stimulus and significantly contrasted ($p < 0.05$) with Breathing and Leaves Rustling.

Task 2: Stimuli Effect on Valence and Arousal
Purring was significantly more pleasant ($p < 0.05$) than Bubbles and Breathing. Heartbeat has the same relationships with both and was slightly less pleasant then Purring, though didn't significantly contrast with it.

Babbling Brook was significantly less arousing than every stimulus except for Crashing Waves, the only other stimulus with a negative arousal rating. Bubbles was significantly more arousing ($p < 0.05$) with 4 other stimuli, Breathing, Leaves Rustling, Crashing Waves and Babbling Brook and had the highest arousal (1.28).

Comparing Task 1 and Task 2
In Task 2, participants on average found Breathing less pleasant (see Table 3) versus Task 1, while Babbling Brook, Heartbeat, Crashing Waves and Purring were more pleasant once identified. Babbling Brook became less arousing after being labelled in Task 2. Bubbles became the most arousing stimuli in Task 2 by a margin of 0.647.

Correlations between Accuracy and Arousal or Valence
We found a significant positive correlation between accuracy and valence ($cor = 0.162$, $p < 0.001$). This link is, however, influenced by Heartbeat with 93.3% accuracy and the highest valence of 0.917. The recognition of this stimulus may have contributed to its valence but as the only stimulus with over 27% accuracy it may be an outlier. It should also be noted that Heartbeat was made up of strong rhythmic pulses, so its recognition may be derived from its distinctiveness when compared to other stimuli with softer, noisier waveforms. The Qualitative data, however, suggests the majority of users felt the Heartbeat was resonant, not just distinct.

5.2.1 Qualitative Feedback. Participants had a wide variety of opinions on the different stimuli they experienced in both tasks, although some trends did emerge.

When asked whether they felt differently about the experiment or stimuli after being given the identity of each stimulus, 8 participants stated they felt no difference and 8 felt their perception had changed. How this change manifested depended on the participant. 6 participants commented that they found recognisable stimuli in Task 1 even more pleasant in Task 2 as their judgement was affirmed. 5 participants felt that when they discovered they had incorrectly recognised a stimulus it became less pleasant. 6 participants made statements such as "(stimuli were) more pleasant when I had something to associate it with" and "things you thought were not that pleasant, when you hear they are like breaking waves or whatever they feel more pleasant".

The second question asked participants if any stimuli felt resonant and recognisable during Task 2, and inversely which stimuli did not resemble the label given. Some stimuli received several comments, while others were rarely mentioned. The three most resonant stimuli following identification were: Heartbeat, Purring and Bubbles, mentioned by 11, 10 and 8 participants respectively, with no participants contradicting this. Rustling Leaves had a mixed reception, as 4 participants found it resonant, while 4 others still found it to be indistinct. Breathing was mentioned only once as resonant, while 4 participants thought it was too forceful and alerting to be resonant of a soft sensation.

The final question asked participants if any stimuli stood out to them for any reason. 16 participants mentioned the Heartbeat, 12 who liked it and 4 who did not. Those who enjoyed it said it felt "natural", "familiar", "recognisable" and reminded them of feeling heartbeats during social touch. Those who disliked it cited different negative associations. One participant "imagined holding a bloody heart in their hand" and another recalled dissected a heart in school. The second most discussed stimulus was Purring, enjoyed by 9 participants and disliked by 2. The most common reason to mention Purring was a relationship to cats. Several were cat lovers, one commenting "I'm a cat lover and when I feel purring I think (it's) very nice". The other stimuli mentioned by several participants were Bubbles and Breathing. Bubbles had mixed feedback, some felt it was true to the original sensation, while others felt it was "too intensive" to be resonant. Breathing was disliked by all but 1 of the 7 who mentioned it, one commenting it felt intense and unhealthy. Every participant mentioned at least one stimulus they found resonant and enjoyed, with an average of 2 stimuli each.

6 DISCUSSION

6.1 Effect of Duration on Affective Responses

Fig. 5 shows the mean valence and arousal ratings for Tactons at a duration of 2 seconds and 20 seconds. While affective responses to some stimuli did change following the duration increase, our analysis found no significant main effect of duration. This could indicate that longer stimuli can be employed without negatively impacting valence or arousal, although habituation effects must be considered. The interaction effect we found (see Fig. 4) suggested that the 20 second stimuli may be more pleasant at higher frequencies than the 2 second ones. This could be attributed to the higher arousal associated with lower frequencies found by this and previous studies [13] and the effects of habituation. 7 participants mentioned the sensation deadening during the 20 second stimuli and this may have led to reduced arousal and subsequent increased valence for low frequencies. We did not find an interaction effect between arousal and duration, however, so the cause of the effect shown in Fig. 4

is unclear. Future work investigating affective responses to more intermediate levels of duration would help to identify at what point habituation effects set in and if prior to these effects duration does have a significant effect on emotional response.

6.2 Emotionally Resonant Cues

The findings support our hypothesis that participants would form emotional associations with stimuli they found resonant, with every participant finding at least one stimulus resonant of the original sensation and forming an emotional association with it. These associations ranged from personal experiences ("I have a cat and cat purring is great") to more abstract emotional reactions ("The Heartbeat felt creepy") and sometimes had surprising origins, such as one participant's negative connection between Babbling Brook and Macbeth ("I associate them with witches. I think back to Shakespearean things"). This highlights that the effects of emotional resonance can be powerful but also very individual.

Qualitative feedback shows that giving labels to the stimuli in Task 2 allowed participants to recognise them more clearly and find them more resonant. In Task 1, all but one of the stimuli had a recognition accuracy of <=27%. This suggests that some emotionally resonant vibrotactile cues cannot 'speak for themselves', but the affordance of labelling stimuli still allows for emotional resonance. It also strengthens the case for designing artificial stimuli alongside users that represent natural sensations to observe if they are more recognisable.

The stimuli set contained a variety of waveforms, some featuring a series of staccato pulses (Heartbeat, Purring, Bubbles) and others a smoother, continuous form (Leaves Rustling, Crashing Waves, Babbling Brook, Muffled Conversation, Breathing). These smoother stimuli tended to be less arousing, but there was no clear trend in which group was more pleasant, as Babbling Brook and Heartbeat were significantly more pleasant in Task 1 than Breathing and Bubbles, while Purring was significantly more pleasant than Bubbles in Task 2.

The range of emotional responses was similar to that achieved by the abstract stimuli from Study 1 (see Fig. 5). The majority of stimuli were grouped towards the top-right and bottom-right quadrants of the Circumplex Model (see Figs. 2 and 7), indicating the stimuli were overall somewhat pleasant and slightly alerting, with a valence range of -0.367 to 1.05 and an arousal range of -1.07 to 1.28. Taking our qualitative analysis into consideration, we theorise that the subjectivity of emotional resonance as a result of individual's personal experiences contributed to these narrow affective ranges, as affective ratings by those who have no emotional attachment to a specific sensation were averaged with ratings left by individuals who held an emotional attachment.

6.3 Personal Experiences and Resonance

The concept of emotionally resonant stimuli relies on the user recognising a simulated sensation and it reminding them of an emotional association they have with that sensation. Thus, emotional resonance of a stimulus is reliant on the user having a personal connection to it. Finding the average affective responses to these cues is problematic if all the users surveyed do not share that connection. For example, during interviews 10 participants found Purring resonant and 9 of those enjoyed the stimulus, 5 citing that they were cat lovers or owners. Had only these participants rated this stimulus it would changed its valence value. By considering each user's personal experiences, emotionally resonant stimuli could be tailored to achieve specific emotional responses and this may allow vibrotactile cues to exceed their narrow affective range. Eliciting emotion using resonant sensations would allow UI designers to calibrate vibrotactile stimuli to users based on the real-world sensations they have attachment to.

In our study, the stimulus with the highest recognition accuracy, most resonance and the most discussion, was the Heartbeat, a universal human experience which also naturally presents as a haptic sensation. Several participants echoed the negative associations found by Handscomb *et al.* [12], commenting it brought to mind gruesome or unpleasant imagery. Others associated the Heartbeat with naturalness, social touch, a soothing rhythm, an internal recognition of stress, or simple familiarity. Even if a sensation is resonant and recognisable for the majority, those emotional associations can still be positive or negative. There may be no stimulus which can evoke a specific emotion in everyone.

There are several avenues for further research on the topic of emotionally resonant vibrotactile stimuli. The Heartbeat was the most recognisable and resonant stimulus in this study and it would be valuable in future work to observe the affective response to other variations, such as a faster heart rate. A key question for further investigation is if there are more stimuli like this one.

There may be other possible real-world sensations that could be used as emotionally resonant vibrotactile stimuli. One approach to developing these stimuli is, considering the importance of personal experience in emotional resonance, to co-design with participants based on their preferences, then observe if those stimuli can effectively evoke the sensations the co-designers suggested.

Finally, it would be valuable to run a comparison study observing how additional elements like texture or temperature affect the emotional resonance of stimuli. Previous research into the affective properties of temperature and texture have shown that warmth and smoothness tends to be perceived more positively than cold and roughness [9, 10, 33]. It would be interesting to observe if this remains true even if, for example, a warm temperature is presented alongside an emotionally resonant stimulus which evokes a cold sensation, theoretically disrupting its resonance.

7 CONCLUSION

This paper presented the first observation of affective responses to emotionally resonant vibrotactile stimuli that evoke real-world sensations. The affective range of these stimuli was similar to that of traditional abstract Tactons, however, some stimuli did succeed in being emotionally resonant for participants, particularly if they had some prior emotional connection to the sensation it evoked. Labelling stimuli allowed participants to better comprehend and make emotional associations with them and these associations varied depending on that individual's personal experience. This research introduces a novel way to elicit emotion in users using vibrotactile cues that draw on their emotional connection to real-world sensations and could allow designers to use an individual's personal experiences to create rich and emotional touch interfaces.

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