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Investigating crossmodal correspondences between vibrotactile stimuli, colour, and emotions☆

Isabel Neto [a,b,*], Isabel Soares [c], Ana Paiva [b], Hugo Nicolau [c]

[a] LASIGE, Faculdade de Ciências, University of Lisbon, Portugal
[b] INESC-ID, Instituto Superior Técnico, University of Lisbon, Portugal
[c] ITI, LARSYS, Instituto Superior Técnico, University of Lisbon, Portugal

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ABSTRACT

There is an increasing interest in Human–computer Interaction in multisensory interactive systems, creating a need to deepen our understanding of how multiple sensory modalities relate to and affect each other. We extend prior research on crossmodal correspondences by investigating colour and emotional associations with pure vibrotactile stimuli. We asked 32 participants to assign colour properties (hue and brightness) and emotional categories (pleasure, arousal, and dominance) to stimuli of varying amplitude and angular frequency. We found that perceptions of pleasure and arousal increased with amplitude and angular frequency, but negative and relaxing emotional states were not able to convey. We also found associations between vibrotactile stimuli and colour properties. High amplitude stimuli were linked to warm colours and darker shades, while low amplitude was associated with brighter shades and greater variance in hue. We finish by discussing the causal mechanisms of crossmodal correspondences and contribute a design space for creating multisensory experiences.

1. Introduction

In the last decade, we have witnessed an increased interest in multisensory experiences or, more broadly, the role of different human senses when designing interactive experiences. Indeed, using multi-sensory stimuli can lead to novel forms of engagement, realism, and inclusion (Antunes et al., 2022; Dmitrenko et al., 2017; Ranasinghe et al., 2018; Narumi et al., 2011). Particularly, researchers have been increasingly exploring the sense of touch: from vibrotactile and thermal feedback of mobile and wearable devices (Israr and Poupyrev, 2011; Wilson and Brewster, 2017) to force feedback (Jeong et al., 2004; Neto et al., 2020), texture changing interfaces (Hu et al., 2018; Feng et al., 2022), and electrical muscle stimulation in mixed reality (Lopes et al., 2018). However, to combine multiple sensory modalities properly, i.e. create effective multisensory experiences, designers need to understand how different modalities relate to one another and influence each other. In Human–Computer Interaction (HCI), prior work has proposed and demonstrated how the study of multisensory experiences should be grounded in crossmodal correspondences to characterise the relationship between sensory modalities (Lin et al., 2021; Feng et al., 2022; Metatla et al., 2019a). Crossmodal correspondences are defined as nonarbitrary associations across perceptual modalities (Spence, 2011). A large body of research from cognitive sciences shows that mappings between sensations across a wide range of sensory modalities are common in the general population (Spence et al., 2015; Velasco et al., 2016; Ramachandran and Hubbard, 2003; Ho et al., 2014; Parise and Spence, 2012; Rinaldi et al., 2018). Examples include perceptual associations between visual shape size and auditory pitch (Parise and Spence, 2012), temperature and colours (Ho et al., 2014), smell and spatial attention (Rinaldi et al., 2018), and taste and shape (Velasco et al., 2016). More recently, researchers have shown associations between haptic experiences, using 3D-printed and shape-changing objects (Lin et al., 2021; Feng et al., 2022), and colour. Moreover, they show that crossmodal correspondences can also reveal at a more abstract level, relating sensory properties (e.g., tactile "spikiness") to emotions (Spence, 2011; Lin et al., 2021; Metatla et al., 2019a; Feng et al., 2022). Further investigating haptic crossmodal correspondences can tell us more about how different aspects of our senses are interlinked and can have applied effects in the fields of design, aesthetics, and multisensory experiences.

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* Corresponding author at: INESC-ID, Instituto Superior Técnico, University of Lisbon, Portugal.
E-mail address: aineto@fc.ul.pt (I. Neto).

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We contribute to the body of work of crossmodal correspondences by examining mappings between vibrotactile stimuli, colour, and emotions. We focus on vibrotactile feedback as it is often used to complement other senses in multisensory experiences. Furthermore, it is a cheap, robust, easily programmable, and widely available interactive modality. It can be incorporated into multiple off-the-shelf devices, such as mainstream mobile devices, controllers, wearables, AR/VR headsets, smart objects, and robotic devices. Still, we lack an understanding of how vibrotactile stimuli relate to other perceptual modalities, namely visual perception. Particularly, colours are often used in computer interaction to structure content, differentiate objects, make aesthetic choices, and enhance the overall experience. Furthermore, colours may have a cultural and emotional meaning (e.g., red to indicate danger or love) to enable affective communication in HCI (Frey et al., 2018).

In this paper, we leverage the methodological approach to study crossmodal correspondences proposed by Lin et al. (2021) and provide an empirical study where we asked 32 participants to associate colour (hue and brightness) and emotional categories (pleasure, arousal, and dominance) with vibrotactile stimuli. The stimuli were designed by manipulating the angular frequency and amplitude within a commonly used sine wave in interactive systems (Delazio et al., 2017; Nicolau et al., 2013; Wilson and Brewster, 2017). The final set of stimuli comprised 18 models of varying amplitude (3 levels) and angular frequency (6 levels).

The key contributions of this paper are: (1) an extension of previous work on crossmodal correspondences and new empirical evidence associating vibrotactile characteristics with colour and emotional dimensions, and (2) a crossmodal correspondences design space for creating multisensory experiences that allow designers to select vibrotactile stimuli that are closely related to colourful experiences or trigger specific emotional precepts.

2. Related work

We discuss related work along three key topics: first, we analyse crossmodal correspondence research, particularly within HCI. Second, we describe previous studies that investigate tactile-visual mappings. Finally, we present prior research in both tactile and visual affective feedback.

2.1. Crossmodal correspondences

Humans perceive the world using their different senses by combining concurrent stimuli. However, it is still hard to know how each stimulus can relate and how humans sense it (Spence, 2011). Crossmodal correspondences refer to the compatibility effect perceived by the general population of the concurrent stimulus attributes with the different sensory modalities (Spence et al., 2015; Velasco et al., 2016; Ramachandran and Hubbard, 2003; Ho et al., 2014; Parise and Spence, 2012; Rinaldi et al., 2018). Previous research has attributed crossmodal correspondences to four main causes (Parise and Spence, 2012; Spence, 2011): *affective* where associations between two dimensions are based on similar emotional valences; *semantic* correspondences, which are based on similar meanings between dimensions; *statistical*, which depend on sensory patterns built through experience; and *structural* correspondences are innate or exist due to maturing of sensory coding structures. Correspondences are more likely to occur the closer the stimuli are presented in time and space (Spence, 2011), and are often shared across ages and cultures.

Crossmodal correspondences can vary from a low-level physical attribute correlation such as temporal, space or synaesthetic (e.g., associations between pitch, lightness, brightness, and size) to a high-level cognitive correspondence based on meaning and pleasure, such as semantic or emotional. One example is the correlation of audio with brightness, space, colours, and shapes. High-pitched tones are more likely to be matched to brighter surfaces, yellow colour, and a higher space location (Spence, 2011; Parise and Spence, 2012). Another example is the associations humans tend to make between sounds and shapes. A typical example is the Bouba/Kiki effect, which illustrates a visio-linguistic correspondence (Ramachandran and Hubbard, 2003). Considering two drawings, one looks like a jagged piece of shattered glass and the other an inkblot consisting of rounded curves. When asked, "Which of these is 'Bouba' and 'Kiki'?" 97% of people pick the inkblot as Bouba and the other one as Kiki. At a pleasure level, emotions can also relate to scents and shapes (Metatla et al., 2019b; Collier, 1996). Angular shapes and lemon scent elicit arousing emotions while round shapes and vanilla scent relate with calming emotions (Metatla et al., 2019b).

When designing interactive systems, it is crucial to be aware of the Crossmodal correspondences between multiple feedback modalities as the combining effect may (positively/negatively) affect the experience. A user interface's colour and its elements impact many perceptual attributes, namely the weight, temperature, speed, and relevance (Löffler, 2017). Similarly, vibrotactile feedback is also often used to enhance user experience. It can improve input accuracy (Hoggan et al., 2013), create safer driving experiences by replacing the visual cues of a car touchscreen (Bernard et al., 2022) or improve affective communication by enriching facial expressions (Bonnet et al., 2011).

Overall, HCI has increased interest in exploring crossmodal correspondences, particularly when considering multisensory experiences. We build on this body of work by investigating associations between vibrotactile stimuli, colour, and emotions.

2.2. Tactile-visual associations

There are no physical link between the sensory mechanisms of colours in the retina, and vibrotactile perception triggered by mechanoreceptors in the skin. Still, this perceptual split does not prevent the formation of haptic-colour associations at more central cognitive levels. Indeed, these associations have been previously demonstrated where colours could represent various haptic stimuli (Spence, 2011; Slobodenyuk et al., 2015; Steer et al., 2023) including texture, shape, stiffness, force feedback, temperature, electric stimulation, and vibrotactile stimuli.

Slobodenyuk et al. (2015) investigated crossmodal correspondences between colour and various haptic-feedback stimuli with variations in the intensity of roughness-smoothness, heaviness-lightness, elasticity-in-elasticity, and adhesiveness-non-adhesiveness. Results showed that the brighter shades are associated with less intense stimuli (i.e the smoothest, the lightest and the most elastic and most adhesive), and the darker shades relate to most intense haptic sensations (i.e. the heaviest, the roughest, the hardest, the most inelastic, and the most adhesive stimuli). In terms of hue, high intensity stimuli showed a trend towards red, violet and blue while yellow and green were often associated with low-intensity stimuli.

More recently, research has investigated crossmodal correspondences between active haptic exploration of 3D objects and colour (Lin et al., 2021; Feng et al., 2022). Results show a trend to associate high degrees of complexity and angularity with red colours and low brightness. On the other hand, less complex round objects were associated with blue colours and high brightness. Interestingly, these findings on 3D objects contrast with crossmodal effects triggered by 2D shapes. However, some authors argue that further research is needed to fully understand crossmodal correspondences between shape and colour due to the lack of replicability and consistency of findings (Dreksler and Spence, 2019), which also applies to crossmodal correspondences with vibrotactile stimuli.

Despite the ubiquity of vibration motors in consumer devices, we witness a lack of research in Crossmodal correspondences between vibrotactile feedback and colour. An exception is Delazio et al. (2017) work. The authors found a trend for low-frequency vibrations to be associated with violet or red as the amplitude increased, while high-frequency vibrations moved from green to red with increasing amplitude. Similarly to other types of haptic feedback (Slobodenyuk et al., 2015; Ludwig and Simner, 2013), results showed a negative relationship between brightness and vibrotactile frequency.

We extend prior research on crossmodal correspondences by systematically investigating both colour and emotional associations with pure vibrotactile stimuli of varying amplitude and angular frequency.

2.3. Tactile and visual affective feedback

Overall, emotion emerges from appraisals of events, which involves an evaluation process that originates a response (emotion) (Cornelius, 2006). The most common conceptualisation of emotion is the three-dimensional pleasure (emotional pleasantness), arousal (emotional excitation), and dominance (feeling of control) framework (Mehrabian, 1995). Understanding how to elicit emotional reactions to an object or event has been the focus of much HCI research.

Vibrotactile feedback has been previously explored to convey emotion, particularly as a nonvisual feedback modality. Short and rapid vibrotactile stimuli are often associated with higher arousal levels (Macdonald et al., 2020; Seifi and MacLean, 2013; Yoo et al., 2015). Stimuli's frequency and amplitude have the potential to used to convey different levels of pleasure and arousal (Macdonald et al., 2020; Seifi and MacLean, 2013; Yoo et al., 2015). Moreover, vibrations are usually perceived as highly arousing, and there is a narrow pleasure range with most stimuli tending towards unpleasant-neutral. More recently, several authors focused on supporting the design of vibrotactile stimuli. For example, Seifi et al. (2015) proposed five taxonomies for describing vibrations to aid designers in navigating a library with diverse functional and affective characteristics. Others have used crowdsourcing (Schneider et al., 2016) or personalised models (Pescara et al., 2020) to streamline vibrotactile design, particularly to convey affective properties. Terenti and Vatavu (2022) presented an authoring tool to facilitate the specification of vibrotactile patterns for mobile and wearable applications. Previous research also explored specific affective vibrotactile applications such as interpersonal communication devices (Ju et al., 2021; Raisamo et al., 2022), and multimodal emoticons (An et al., 2022). Still, understanding how vibrotactile feedback integrates with other senses is largely unexplored.

Prior studies on crossmodal correspondences using tangible objects, either 3D and shape-changing objects, showed associations with the emotional dimensions of pleasure and arousal (Lin et al., 2021; Feng et al., 2022; Hu and Hoffman, 2019; Neto et al., 2024a). The angularity, complexity, size, and changing frequency influence humans' emotional associations. For instance, sharper objects are associated with high arousal levels while rounded shapes elicit positive pleasure levels (Lin et al., 2021). There are exceptions due to the symbolic meaning of shapes, e.g., diamonds' shape, despite being sharp, is related to positive pleasure (i.e., love); similarly, stars are usually related to pride (Collier, 1996).

Other work outside the HCI community has also explored haptics to convey emotion (Hu and Hoffman, 2019; Song and Yamada, 2017; Neto et al., 2024a,b). In psychology, Sehlstedt et al. (2016) showed that touch-pleasantness perception increases while touch-sensitivity decreases through life. Hertenstein et al. (2006) explored human interpersonal touch, showing that by changing the body zone contact, pressure, and rhythm, touch can express very different emotions, from human bonding and comfort while holding hands to aggression with slapping. In Human–Robot Interaction (HRI), robotic devices can convey happiness using colour-motion combinations by blinking lights and using fast movements. Sadness can be conveyed by a sound and motion of a falling beep and slow movements, while fear is better perceived using hiding movements and red lights. Anger can be expressed with high vibrotactile amplitude (Löffler et al., 2018). Material properties have also been explored in HRI to convey emotions. Sato et al. (2020) investigated the use of multiple materials (e.g., plastic resin, aluminium, clay, velcro, and cotton) with different temperatures, and contact patterns (i.e., tap fast, tap slowly, stroke fast or stroke slowly) to elicit emotional reactions. For instance, by changing the contact movement, a robot can express excitement and boredom using velcro. Another example in robotics, are soft materials and shape-changing robotic skins could express happiness, calm, anger, and fear. For example, humans convey happiness with soft, hairy, and flexible skins like inflated/deflated tentacles; calm can be conveyed with wrinkles like skins that go from smooth to roughness in a slow movement; and fear and anger can be conveyed by enhancing the soft skin with hard tips that by fast inflating and deflating the skin, humans sensed it as aggressive and frightening (Neto et al., 2024a,b).

Regarding visual affective feedback, much research has explored the use of 2D shapes (Dreksler and Spence, 2019), abstract designs (Valtchanov and Hancock, 2015), complex graphics (Miller et al., 2016), or facial expressions (Bala et al., 2014) or inherent associations of colour to emotional dimensions (Adams and Osgood, 1973; Valdez and Mehrabian, 1994; Whitfield and Whiltshire, 1990). For instance, according to Valdez and Mehrabian (1994), blue, green, and purple are associated with high levels of pleasure, whereas yellow with the lowest levels of pleasure. Green and yellow are the most arousing hues, while purple–blue and yellow–red are the least arousing. However, these associations can be influenced by cultural differences, individual preference, and concurrent sensory modalities (e.g., haptics) (Whitfield and Whiltshire, 1990; Lin et al., 2021; Bala et al., 2014; Neto et al., 2024b).

Vibrotactile experience design is often woven together with other multisensory design efforts (Schneider et al., 2017). However, few studies have examined the multisensory interactions between vibrotactile feedback and other senses. Prior work on vibrotactile crossmodal correspondences either used discrete emotional labels (e.g., sadness) (Song and Yamada, 2017; Obrist et al., 2015), which limits the generability of results, used explicit visual cues such as human facial expressions (Bala et al., 2014), or used abstract visual shapes rather colour properties (Wilson and Brewster, 2017). The present work expands this line of research by investigating how vibrotactile stimuli elicit colour properties (hue and brightness) to create multisensory experiences that influence affective communication.

3. User study

This study aimed to explore the crossmodal correspondences between vibrotactile stimuli, colour and emotions. We used a mixed-methods approach proposed by Lin et al. (2021) that combines the identification of crossmodal correspondences through controlled quantitative experiments, together with qualitative analysis of subjective association strategies. Such an approach enables the collection of richer insights beyond *what* Crossmodal correspondences may exist as well as *how* they are internally created. Thus, we asked subjects to associate specific colours and emotions with a set of vibrotactile stimuli. The vibrotactile stimuli varied in levels of amplitude and angular frequency. Afterwards, we debriefed participants about their association strategies. The research protocol was approved by the Instituto Superior Técnico's Ethics Committee, and participants signed consent forms.

3.1. Participants

Thirty adults, fifteen females and fifteen males, aged between 20 and 38 years (M=23, SD=3.2), volunteered to participate in the user study without being given any reward. They were recruited through opportunity sampling at the local University. Twenty-nine participants reported being right-handed, while one reported being left-handed. All participants reported using vibrotactile feedback on their smartphones. All participants reported having typical sight without experiencing any

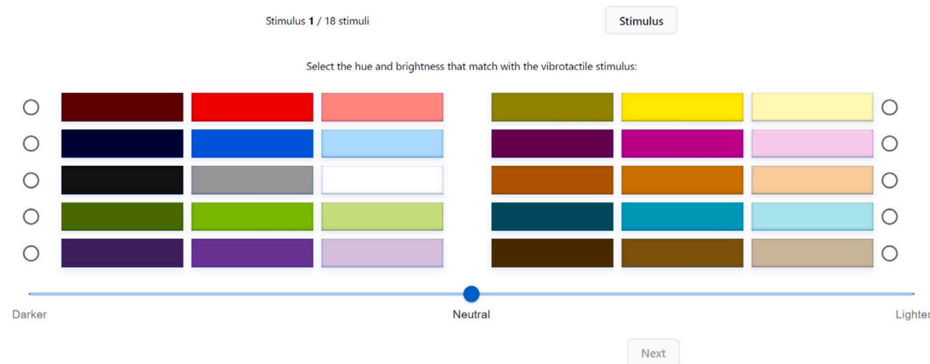

Fig. 1. Web interface presented to participants in the vibrotactile-colour association task. At the top is the colour palette for hue selection, and at the bottom, the brightness selection using a slider.

strong form of synaesthesia (Mylopoulos and Ro, 2013; Ramachandran and Brang, 2008; Saenz and Koch, 2008) (i.e., stimulation of one sensory modality causes a simultaneous stimulation of another, unrelated sensation).

3.2. Task

We followed a within-subjects design where participants performed two tasks in each session: first the *vibrotactile-emotion association* and then, the *vibrotactile-colour association*. Participants experienced 18 vibrotactile stimuli in both tasks, displayed randomly to avoid ordering effects. Each stimulus had a duration of 10 s, as suggested by Macdonald et al. (2020), in order to reduce the habituation effects of a longer actuation. Additionally, participants had some idle time, hands off the device, between stimuli to reduce tiredness, and answered the questionnaire. Participants provided one answer per stimulus for each association task; however, they could repeat the stimuli multiple times via a web interface , similar to previous study procedure (Lin et al., 2021). Participants felt the stimulus by placing their non-dominant hand on top of an object and using their dominant hand to fill the response screen.

In the *the vibrotactile-emotion association* task, participants were asked to associate three emotional scales with each stimulus. We used the nine-point Self-Assessment Manikin (SAM) (Bradley and Lang, 1994), which is a nonverbal pictorial assessment technique that directly measures the pleasure, arousal, and dominance associated with a person's affective perception of the stimuli (Mehrabian, 1995). We asked participants to focus on what they thought the object was emotionally expressing rather than the feeling the stimuli invoked in them. Because people may react differently to emotional expression depending on the interaction context and situation, we wanted to avoid adding an additional layer of interpretation, i.e., what they felt after perceiving the emotional expression of the object. Our goal was to derive guidelines to aid designers in representing affective states through vibrotactile feedback. We did this by asking: "feeling the stimulus with my hand, the object is ..." and then chose the rating that best fit. Thus, results should be interpreted as users' perception of the object's emotional expression. For instance, the Dominance scale was described as how dominant they thought the stimuli were. In addition to the SAM, we also used opposite paired terms for each dimension as recommended for using the Pleasure-Arousal-Dominance Emotional-State Model: Pleasure (pleasant–unpleasant), Arousal (calm-excited), and Dominance (lack of control-in control). This task took, on average, 10.47 min (SD=3.3).

In the *vibrotactile-colour association* task, participants were asked to choose a rating of the hue and brightness of the colour they thought matched the vibrotactile stimulus. Particularly, they were asked to select a colour from a palette of 10 hues (red, blue, grey, green, purple, yellow, pink, orange, aqua, and brown) and select the brightness using a slider (Fig. 1). Hues were inspired based on the five principal (red, yellow, green, blue, purple) and the five intermediate hues of the Munsell Colour System. The palette showed three variations of each hue, representing a darker, neutral, and brighter colour. These colour options cover a wide range of hues and are similar to the ones used in other typical studies assessing colour Crossmodal correspondences (Lin et al., 2021; Dreksler and Spence, 2019). The vibrotactile-colour association task took, on average, 7.14 min (SD=1.4). After, we asked the participants to explain the rationale for their responses. The full interview guide is available as supplementary material. The semi-structured interview took, on average, 4.76 min (SD = 0.5). The duration of the overall study took, on average, 22.37 min (SD=2.0).

3.3. Apparatus

The vibrotactile stimuli were presented to participants through a mushroom-shaped object (Fig. 2). This shape was chosen for two main reasons: (1) to allow participants to rest their hand on the object comfortably, and (2) to provide an embodiment, which facilitates attributing an emotional state in the *vibrotactile-emotion association* task. The object had a neutral grey colour to mitigate the risk of priming participants in the colour association task.

We attached a linear resonant actuator (LRA) vibration motor[1] to the back of the object, which was connected to an Arduino UNO Rev3.[2] We chose an LRA vibration motor as it is commonly used in mainstream devices and has a fast start-up time. A response screen was provided via a web interface on a laptop computer. Participants entered their responses via mouse input. The interface allowed them to repeat the stimulus and initiate the next stimulus presentation.

3.4. Vibrotactile stimuli

We designed 18 vibrotactile stimuli that vary in amplitude (three levels) and angular frequency (six levels). Each stimulus was a sine wave illustrated by Eq. (1) with a 100 Hz sampling rate.

$$y = amplitude * sine(angular - frequency * time) \tag{1}$$

The stimuli design decision was based on the aim to maximise hardware capabilities and user perception. With that in mind, we design the 18 stimuli to have enough haptic-discrimination between them. The highest amplitude level corresponded to the maximum voltage of the microcontroller (5 V). The lowest amplitude level was derived from pilot studies of perceivable vibrotactile stimuli (2.5 V), and the medium amplitude level was the average between high and low levels (3.8 V).

[1] https://www.adafruit.com/product/1201
[2] https://store.arduino.cc/products/arduino-uno-rev3/(accessed in 16th of December of 2021).

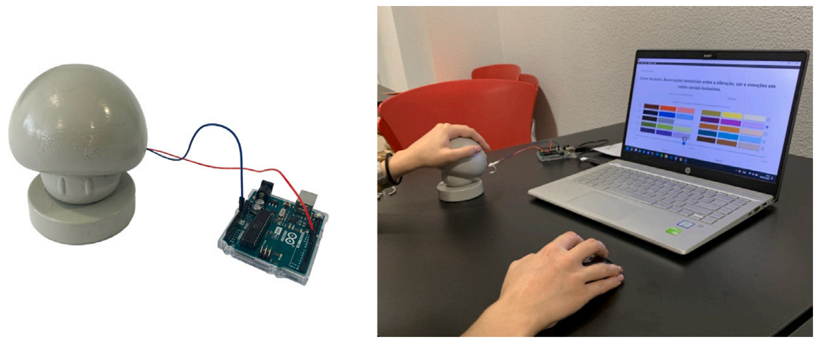

Fig. 2. Experimental setup. On the left is the prototype used in the study, and on the right is a participant during the experiment.

The frequency of the vibrotactile stimuli was varied by increasing the angular frequency of the sine wave. We explored six levels of angular frequency, defined by the total number of cycles in 10 s: 2, 4, 8, 16, 32, and 64 cycles (represented as F2–F64), which incrementally alter the wave along a gradient from 2 to 64 peak amplitudes.

3.5. Procedure

The study took place in a quiet room to minimise distractions and guarantee similar experimental conditions between participants. Participants sat comfortably in a chair in front of a table with a laptop computer, mouse, and vibrotactile object. We placed the vibrotactile object on the side of their non-dominant hand and the mouse on the dominant hand's side. We encouraged participants to put their hand's palm on top of the object and wrap their fingers around it to experience the stimuli. Participants used their palms for the exploration zone as it is typically how humans explore new interfaces. Participants controlled the pace of the experiment through a web interface that allowed them to fill in responses, repeat the stimulus, and advance to the next stimulus.

At the beginning of the session, we informed participants that they would be exploring a variety of vibrotactile stimuli and associating emotional scales, and colours with those stimuli. Participants were then familiarised with the web interface, particularly the colour palette and the SAM scale. Afterwards, participants started the experiment and completed the two tasks (i.e., *vibrotactile-emotion association* and *vibrotactile-colour association*). Vibrotactile stimuli were presented randomly. Sessions were audio recorded to collect participants' comments. Moreover, we interviewed participants at the end to collect their rationale for associations.

3.6. Measures and data analysis

In the *vibrotactile-emotion association* task, we applied the nine-point SAM scale (Bradley and Lang, 1994). In the *vibrotactile-colour association* task, we collected the hue from a set of ten different hue colours and brightness values from 0 to 100%. At the end of each task, we audio-recorded the interviews to collect qualitative data.

We performed the nonparametric Aligned Rank Transform (ART) procedures (Wobbrock et al., 2011) on the SAM scores. In brief, these procedures allow the use of factorial ANOVAs on data that initially do not fulfil all the required assumptions (e.g., continuous dependent variable, normally distributed data). This preliminary step ensures that the resulting ANOVA will have main effects and interactions with appropriate Type I error rates and suitable power. In their most recent work, the authors extended the ART approach with an additional procedure (ART-C) developed to facilitate post-hoc pairwise comparisons (Elkin et al., 2021). In this paper, we applied both procedures to SAM scores.

We then used å mixed-effects model analysis of variance to determine the associated effect of the two independent variables (angular frequency and amplitude) on the three emotional ratings (pleasure, arousal, dominance). Mixed-effects models extend repeated measures models, such as ANOVAs, to allow time-varying covariates; that is, variables that were not controlled during data collection but can influence the outcome of the experiment. In our case, we modelled the number of repetitions per stimulus as a covariate. We found no significant effects of the covariate variable on emotional ratings. Nevertheless, all reported results are controlling for the number of repetitions per stimulus. We first analyse interactions between factors, i.e. angular frequency and amplitude; if no statistically significant interaction was found, we report the main effects. We used Bonferroni corrections while examining the differences between amplitude and angular frequency levels by multiple pairwise comparisons. We also computed polynomial contrasts to analyse the correspondences between vibrotactile stimuli characteristics and emotional ratings by a linear relationship.

Concerning the *vibrotactile-colour associations*, we used a similar approach to other authors that analyse shape-colour associations (Dreksler and Spence, 2019; Lin et al., 2021). Our experimental design was identical to theirs, particularly in terms of colour palette and the number of available colours. Thus, we leveraged the same method of analysis using Pearson's Chi-Square test. We calculated the expected frequency of colour ratings for each stimulus separately. Next, we calculated adjusted standardised residuals, which indicate whether the frequency of colour associations was greater than expected. Standardised residuals greater than two suggest that the colour was selected more frequently than expected by chance (Dreksler and Spence, 2019). For brightness, we ran a mixed-effects model with the number of repetitions per stimulus as a time-varying covariate.

Regarding the interviews, we transcribed the audio recordings to analyse the qualitative data. We then conducted a thematic analysis with an inductive coding approach. One researcher created the initial codes of the transcriptions while producing an affinity diagram to find general patterns about participants' main association strategies. We then conducted a peer validation process, where two researchers discussed, and reviewed codes and emerging themes.

4. Results

Our goal is to understand associations of vibrotactile stimuli with colour characteristics and emotional dimensions. The following sections describe the results on each of the association tasks: *vibrotactile-emotion association* and *vibrotactile-colour association*. Finally, we present findings related to the rationale and strategies used by participants to make such associations.

4.1. Vibrotactile-emotion association

We assessed vibrotactile-emotion associations in terms of ratings for three separate emotion categories: Pleasure, Arousal, and Dominance.

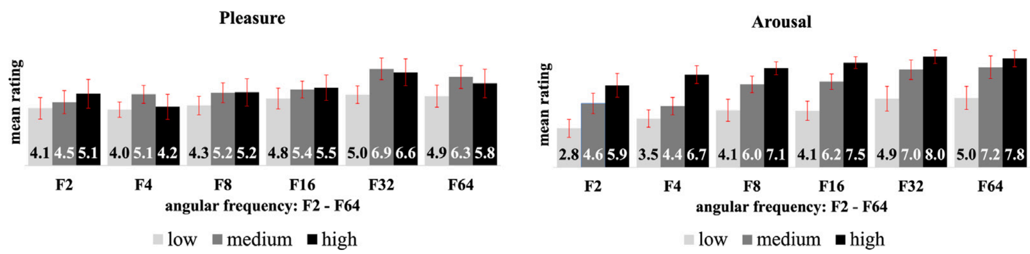

Fig. 3. Mean ratings of pleasure (left) and arousal (right) across three levels of amplitude (low, medium and high) and angular frequency (number of cycles in 10 s: 2, 4, 8, 16, 32, and 64 cycles, represented as F2–F64). The neutral point is five. Error bars denote 95% confidence intervals.

4.1.1. Pleasure (unpleasant–pleasant)

There was no interaction effect of angular frequency * amplitude $F_{(10,521)} = 1.034, p = .413$ on associated pleasure ratings. However, we found a main effect of angular frequency $F_{(5,521)} = 10.274, p < .001$ and amplitude $F_{(2,521)} = 12.506, p < .001$. There was a statistically significant difference between stimuli with different levels of angular frequency, with the two highest levels showing higher pleasure associations compared to the two lowest levels (Fig. 3). That is, there was a statistically significant increase in pleasure ratings $p < .05$ from stimuli with 2 (4.56 ± 2.33, mean ±standard deviation unless otherwise stated) and 4 cycles (4.4 ± 1.86) to 64 (5.69 ± 2.34) and 32 cycles (6.18 ± 2.11). Regarding amplitude, there was a statistically significant increase in pleasure ($p < .001$) from low (4.5 ± 1.84) to medium (5.58 ± 1.94) and high (5.41 ± 2.58) amplitudes. There was no significant difference between medium (5.58 ± 1.94) and high (5.41 ± 2.58) amplitudes. Although we found statistically significant associations between vibrotactile characteristics and pleasure ratings, it is noteworthy that mean pleasure ratings throughout the study are between slightly unpleasant and mildly pleasant scores (i.e., 4–6.7 ratings). This result suggests that expressing extreme (dis)pleasure through vibrotactile stimuli can be challenging.

We also conducted a polynomial contrasts analysis to further explore the relationship between vibrotactile stimuli characteristics and pleasure ratings. We found a positive linear relationship between pleasure and angular frequency $F_{(1,29)} = 23.65, p < .001$.

4.1.2. Arousal (calm-excited)

There was no statistically significant interaction between factors $F_{(10,521)} = 1.199, p = .289$ on associated arousal ratings. However, we found a significant main effect of angular frequency $F_{(5,521)} = 24.692, p < .001$ and amplitude $F_{(2,521)} = 139.835, p < .001$. The main effect on angular frequency showed a statistically significant difference between the lowest frequency stimuli (i.e., 2 and 4 cycles) and all the remaining levels ($p < .05$). On the other hand, the highest frequency stimuli (i.e., 32 and 64 cycles) received overall higher ratings of arousal with significant differences ($p < .05$) to all lowest frequency levels (Fig. 3). In terms of amplitude, we found statistically significant differences between all levels ($p < .001$) with high amplitude stimuli with the highest arousal levels (7.17 ± 1.56), followed by medium amplitude (5.89 ± 1.8), and low amplitude (4.06 ± 2.01). Positive linear relationships were found between arousal and amplitude $F_{(1,29)} = 241.347, p < .001$ and between arousal and angular frequency $F_{(1,29)} = 55.703, p < .001$.

4.1.3. Dominance (lack of control - in control)

There was no statistically significant interaction between angular frequency and amplitude $F_{(10,521)} = .799, p = .63$ on associated dominance ratings. Moreover, there was no significant main effect of angular frequency $F_{(5,521)} = .411, p = .841$ with average dominance ratings ranging from 4.9 (2 cycles) and 5.0 (64 cycles). However, we found a significant main effect of amplitude $F_{(2,521)} = 32.929, p < .001$. We found statistically significant differences between all levels ($p < .05$) with high amplitude stimuli being perceived as the most dominant (5.9 ± 2.2), followed by medium amplitude (5.2 ± 2.03), and low amplitude (4.1 ± 2.2). Overall, participants associated dominance with higher amplitude levels through a positive linear relationship $F_{(1,29)} = 18.347, p < .001$.

4.2. Vibrotactile-colour association

In this section, we report vibrotactile-colour associations in terms of colour hue and brightness.

4.2.1. Colour hue

Results suggest a significant association between vibrotactile stimuli and hue, $\chi^2(153) = 231.376, p < .001$. Vibrotactile stimuli with high amplitude throughout all frequency levels (e.g., 64 cycles, z=3.2; 32 cycles, z=3.4; 16 cycles, z=2.5) were significantly more often associated with warm colours such as red and yellow than any other colours. On the other hand, participants selected a wide range of colours for low-amplitude stimuli depending on the angular frequency. High-frequency stimuli were significantly more often associated with pink (64 cycles, z=2.1) and green (32 cycles, z=2.6) while lower-frequency stimuli were associated with brown (2 cycles, z=2.8) and aqua (4 cycles, z=4.6). For medium amplitude stimuli, we did not find an overarching association pattern with colour. Overall, red and yellow were the colours most frequently associated with vibrotactile stimuli (Fig. 5).

4.2.2. Colour brightness

There was no statistically significant interaction between angular frequency and amplitude $F_{(10,521)} = .481, p = .902$ on associated brightness scores. Results show that colour brightness was generally associated with vibrotactile amplitude $F_{(2,521)} = 32.459, p < .001$. There was a decrease in brightness ratings ($p < .001$) from low amplitude stimuli (62.5 ± 29.4) to both medium (46.6 ± 22.5) and high amplitude (41.2 ± 25.6) stimuli. Participants associated darker shades with higher amplitude vibrotactile stimuli (Fig. 4). Indeed, we found a negative linear relationship between brightness and amplitude $F(1,29) = -13.524, p < .001$. We also found a significant main effect of angular frequency on brightness ratings $F_{(5,521)} = 2.86, p < .05$. Pairwise comparisons showed a statistically significant difference ($p < .05$) between the lowest frequency of 2 cycles (42.4 ± 27.8) and the highest frequency of 64 cycles (55.6 ± 28.9). Moreover, results indicate a negative linear relationship between colour brightness and angular frequency $F(1,29) = -5.7, p < .025$.

4.3. Association strategies

In this section, we report on the main strategies for both association tasks: *vibrotactile-emotion* and *vibrotactile-colour*.

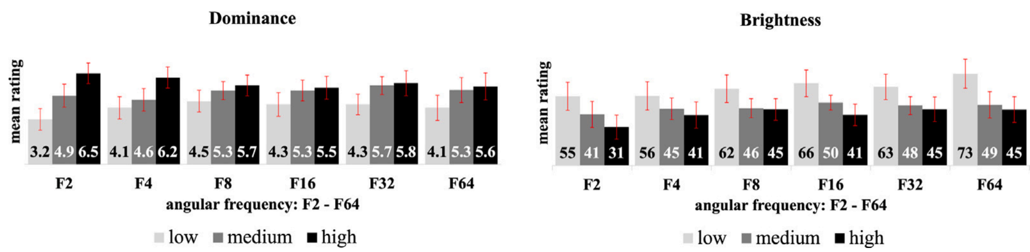

Fig. 4. Mean ratings of dominance (left) and brightness (right) across (low, medium and high) and angular frequency (number of cycles in 10 s: 2, 4, 8, 16, 32, and 64 cycles, represented as F2–F64). The neutral point in dominance perception is five. Ratings of brightness vary between 0 (darker) and 100 (brighter). Error bars denote 95% confidence intervals.

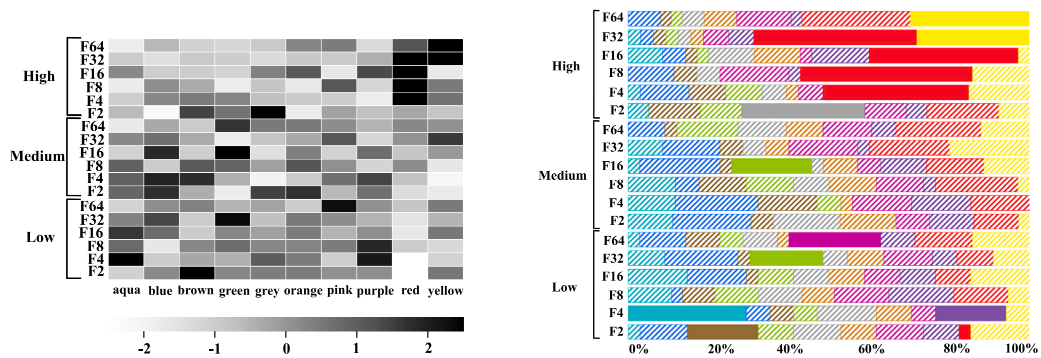

Fig. 5. Pearson's chi-square results. On the left is a heatmap of adjusted standardised residual values of each stimulus. On the right, is the colour percentage of participants' choices for each stimulus. Each bar represents a hue from the study's colour palette. Solid-coloured bars represent an adjusted standardised residual value greater than two.

4.3.1. Vibrotactile-emotion association strategies

Most participants (n=30) were able to explicitly express their rationale for vibrotactile-emotion associations. We categorised their strategies in two broad themes: (1) **Stimuli Characteristics** where the strategy was directly linked to the vibrotactile features, and (2) **Everyday Situations**, where participants leveraged familiar activities, objects, and beings to attribute emotional ratings. Participants consistently associated the stimuli characteristics (i.e., angular frequency and amplitude) with specific emotional categories (e.g., pleasure, arousal). For example, participants consistently associated higher frequency stimuli with excitement and lower frequency stimuli with calmness - e.g., *"When the stimuli were faster, I just imagined in my mind someone saying 'go go go', thus more excited"* - P2. There were instances where participants described how stimuli characteristics can complement each other, e.g. *"When it [the stimuli] is stronger [higher amplitude] I associated it with higher levels of arousal, particularly when it was fast. With slower stimuli, even if they were strong, I associated with calmness"* - P9. Still, we found individual differences when associating pleasure and dominance with vibrotactile stimuli. These differences can be partially explained by participants' lived experiences and their affective correspondences to everyday situations. For example, while some associated lower frequencies to pleasantness - e.g., *"those stimuli that were slower really felt like a cat purring, so I associated with pleasure and happiness"* - P4 - other associated to unpleasantness, e.g. *"when it [the stimuli] was faster I associated with happiness and excitement as in a party, otherwise I associated it with being nervous in my workplace"* - P10. Other situations included meditation, where lower frequencies and amplitudes were associated with calmness, happiness, and in control. Finally, some people mapped physiological characteristics to vibrotactile features - *"I associated the vibration to my heart rate; when it was fast I was happy, when it was slow I was sad"* - P10.

4.3.2. Vibrotactile-colour association strategies

28 participants were able to discuss their colour association strategies while four participants described their strategies as *"instinct"*. Four main strategy patterns emerged: (1) **Stimuli Characteristics** where participants made explicit reference to the vibrotactile features of the stimuli to describe their association strategies. For example, stimuli with higher amplitude or angular frequency were often associated with darker and warmer colours - *"The higher the intensity and frequency [of the stimuli], the darker it is"* - P1, *"When the vibration is strong and fast, I related them to warm colours such as brown, red, and yellow. When the vibration is weak it feels like cold and brighter colours such as blue or green"* - P16; (2) **Colour Meaning** refers to associations based on the cultural meaning of colours and their correspondent emotions, e.g. *"Some stimuli felt happy and excited, which relates to yellow, others I perceived them as angry or red, while annoyed corresponds to black and purple."* - P4; (3) **Individual Preference** where participants based their associations on individual preference for specific colours, e.g. "I associated pleasant stimuli with pink, which is my favourite colour" - P13; and (4) **Lived Experiences** where participants chose colours that reflected lived experiences, e.g. *"Unpleasant vibrations are like going to the dentist, which reminds me of red. Darker red when the vibration is faster, and lighter when is slower"* - P6, *"I associated stronger vibrations with my sports team and their colour is red. Going to the games is always an intense and crowded experience"* - P13.

5. Discussion

This paper explores crossmodal correspondences between vibrotactile properties and emotional and colour dimensions. Our goal is to inform the design of multisensory interactive systems that are able to combine visual and nonvisual stimuli to elicit specific emotional precepts. We extend prior work on crossmodal correspondences by systematically investigating varying levels of amplitude and angular frequency of pure vibrotactile stimuli and their effect on colour and emotional mappings. In the following sections, we discuss our results in light of previous research on vibrotactile feedback, and crossmodal correspondences on haptics. Finally, we contribute with a design space to help designers interpret crossmodal correspondences in HCI.

5.1. Vibrotactile-emotion association

Pleasantness perception increases with amplitude and angular frequency. Our findings showed crossmodal associations as we found mappings between vibrotactile properties and the emotional dimensions of pleasure, arousal, and dominance. Results showed that there exists an *angular frequency-pleasure association*. Particularly, stimuli with increased angular frequency were associated with higher levels of pleasantness. We also found an association between *amplitude-pleasure* with perceived pleasantness increasing with amplitude level; however, results suggest that higher amplitude may not be always better, particularly when combined with high angular frequency. In this case, the perception of pleasure tends to decrease. Comparing these findings with previous experiments investigating vibration-affect associations, we find similarities and contrasting results. Similarly to prior research (Macdonald et al., 2020; Wilson and Brewster, 2017; Seifi and MacLean, 2013), the range of pleasure ratings is limited and conveying a wide range of pleasure levels through vibration can be challenging. However, while vibrotactile stimuli were previously reported as unpleasant-neutral (Seifi and MacLean, 2013), our results are within the slightly-negative to slightly-positive range.

Medium amplitude stimuli express positive pleasure. It is noteworthy that the average pleasure rating was ±2 of neutral ratings, meaning most stimuli were perceived as conveying both pleasant and unpleasant emotions, depending on the participant. These then can cancel each other resulting in a more neutral mean value, which means individual differences play a critical role. Thus, we analysed the reliability of each stimulus by looking at how often it was rated as pleasant (pleasure > 5) or unpleasant (pleasure < 5). Prior research considered 75% as an appropriate threshold to deem a stimulus reliably pleasant or unpleasant (Brewster et al., 1995; Brown et al., 2006; Wilson et al., 2012). Contrasting previous research, we did not find a reliable stimulus to convey negative pleasure. However, medium and high amplitude stimuli (with 32 cycles) were reliably rated as pleasant (i.e., above neutral). Higher and lower amplitudes/angular frequencies are close to chance levels (20%–60%). We hypothesise that these differences to prior research may be related to stimuli design.

Arousal is positively associated with amplitude and angular frequency. We found associations between *amplitude-arousal* and *angular frequency-arousal*. The arousal level increased (perceived as more excited) as the vibrotactile stimuli increased in amplitude and angular frequency. Our results replicate previous research by showing that vibration is highly effective in conveying neutral-high levels of arousal and is positively related to both vibrotactile properties (Wilson and Brewster, 2017). This result means that expressing relaxing emotions (either positive or negative) through vibration can be challenging. Indeed, within our stimuli, only the lowest amplitude and frequency stimulus (2 cycles and low amplitude) was reliably rated as low arousal (i.e., 75% of ratings below neutral). On the other hand, all high amplitude stimuli above F4 frequency (F8H, F16H, F32H, and F64H) and medium amplitude stimuli above F16 frequency (F32M, and F64M) are reliably perceived as conveying excited emotional states.

Convey dominance with higher levels of amplitude. Overall, angular frequency and amplitude influence both pleasure and arousal perceptions simultaneously, with increases in either property increasing both emotional dimensions. In terms of dominance, there is little research exploring the effect of vibrotactile associations. Results show that perceived control was associated with increased amplitude. This perception is most visible in low angular frequency stimuli. Overall, it means that the *vibration-dominance* association is more effective with varying amplitude in lower angular frequency stimuli.

5.2. Vibrotactile-colour association

High amplitude stimuli elicit warm colours. Findings link specific stimuli to a specific colour or set of hues. Indeed, results show a vibrotactile *amplitude-hue* association, particularly stimuli with high amplitude and angular frequencies between F4 and F64 are mostly mapped to warm colours (i.e., red and yellow). On the other hand, lower amplitude stimuli show high variance in hue associations, suggesting that such relationships are highly user-dependent and can be mediated by multiple individual factors. Similar results have been reported in the case of shape-colours correspondences (Dreksler and Spence, 2019; Malfatti, 2014)

Negative relationship between amplitude and brightness. Results showed that there exists a negative amplitude-brightness association independent of the angular frequency of the stimuli. Higher amplitude vibrotactile stimuli are associated with darker shades, while lower amplitude stimuli are mapped to lighter shades. Moreover, results show a gradient in the association, in which brightness decreased with increasing amplitude. This finding goes in line with other haptic-brightness associations (e.g., 3D shapes and force-feedback), where brightness decreased with "rougher" shapes (Lin et al., 2021; Slobodenyuk et al., 2015). On the other hand, it contrasts with results on correspondences with 2D shapes in which brightness increases with high pitch (Walker et al., 2012). In the visual domain, "rougher" or more angular shapes have been associated with higher brightness. Thus, haptic crossmodal correspondences seem to follow unique principles and cannot be extrapolated from the visual domain.

5.3. Causal mechanisms of associations

We found consistent crossmodal associations between vibrotactile stimuli, emotional categories, and colour properties. Qualitative analysis of participants' self-reported association strategies revealed links to stimuli features and lived experiences. Moreover, in colour associations, participants also leveraged cultural meanings of colour and individual preference. These results indicate that whatever choices individuals make regarding emotional categories or colour features associated with vibrotactile stimuli, they seem to be driven by affective appraisals and preferences. These findings go in line with previous work exploring the nature of crossmodal correspondences (Spence, 2011). Affective correspondences are associations of two dimensions based on similar hedonic responses; for instance, vibrotactile stimuli are associated with relaxing situations (e.g., massage, cat pouring) or excitement (e.g., parties, drilling) depending on the amplitude and angular frequency.

We also found participants making associations, particularly vibration-colour associations, due to the emotional meaning of colours. This result also suggests emotionally-mediated associations and transitional features between crossmodal correspondences, where vibrotactile stimuli are associated with specific emotional appraisals, and these are associated with colours. For example, high amplitude stimuli are associated with pleasantness and, thus, associated with warmer colours and darker shades. Similarly, previous research on crossmodal correspondences already suggested transitional features between shape's angularity - pleasure - brightness (Lin et al., 2021).

Although emotional appraisals seem to play a relevant role in the mechanisms that underlie vibration-emotion and vibration-colour associations, nonemotional concepts, such as preference, also contribute. It is the case when participants associate pleasant stimuli with the colour they like the most. Overall, participants often choose colours they liked for stimuli they liked, as well as colours more emotionally consistent in their associations with the vibrotactile stimuli that aligned with these emotional associations (Chen et al., 2016).

Even though our study cannot quantitatively confirm the inherent nature of crossmodal correspondences, it sheds light on its potential causes, which are consistent with current models of cognitive sciences and multisensory research (Spence, 2011; Chen et al., 2016). Moreover, we confirm that vibrotactile amplitude and brightness share the same emotional pleasure and arousal.

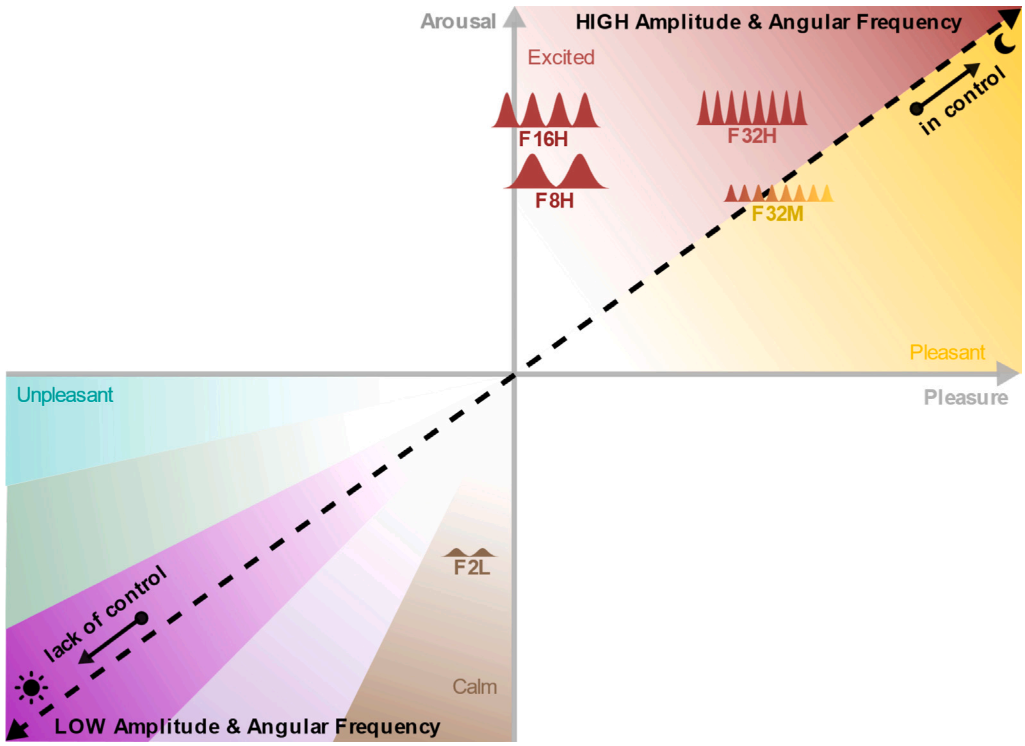

Fig. 6. Design Space for Vibrotactile and Visual Crossmodal Correspondences. The sun icon illustrates higher levels of brightness while the moon represents the darker shades.

5.4. A design space for vibrotactile and visual crossmodal correspondences

Design spaces have been previously proposed in HCI across multiple technologies: from input devices and smartphones (Card et al., 1990; Ballagas et al., 2006; Nicolau et al., 2019) to shape-changing and voice user interfaces (Kwak et al., 2014; Metatla et al., 2019b). They are often used to synthesise knowledge, highlight research gaps, and guide designers in shaping new products or services.

Indeed, design spaces have been used to synthesise crossmodal correspondences (Lin et al., 2021), particularly to map stimuli properties to the pleasure and arousal model (Mehrabian, 1995). Based on our findings, we present a design space to visually represent the crossmodal links between vibrotactile stimuli, emotions, and colour (Fig. 6). The vibrotactile stimuli properties are mapped to the pleasure (x-axes) and arousal (y-axes) model. Furthermore, we represent the stimuli reliably perceived by participants (i.e., at least 75% of participants rated the stimuli above/below neutral) alongside their hue associations as background.

Results link vibrotactile stimuli to emotional categories (Fig. 6, dashed lines). Particularly, higher amplitude and angular frequency levels are most effective in conveying neutral to positive pleasure and neutral to high arousal emotions. Lower amplitude and angular frequency levels can elicit perceptions of slight unpleasantness and calmness. Amplitude was also linked to dominance, i.e., higher amplitude levels trigger a sense of control. In terms of visual crossmodal correspondences, higher amplitudes were associated with warmer hues and darker shades, while lower amplitude levels were linked to higher levels of brightness and multiple hues (e.g., brown, aqua, pink, and green).

Overall, we articulate a crossmodal correspondences design space for creating vibrotactile multisensory artefacts that can trigger specific emotional precepts. High amplitude/frequency vibrotactile stimuli (F32H) could be combined with low brightness/red to trigger pleasant/aroused/in-control emotions, while low amplitude/frequency stimuli (F2L) could be combined with high brightness/brown to trigger calm emotions. In addition to these guidelines, in Fig. 6, we illustrate the five vibrotactile stimuli that reliably and consistently map to similar values of pleasure, arousal, hue and brightness. Thus, the design space provides actionable design recommendations on how to combine vibrotactile stimuli with colour while highlighting the limited range of reliable emotions that can be conveyed. Reliable perceptions are within two pleasure-arousal quadrants: positive pleasure - positive arousal, and negative pleasure - negative arousal. These results complement prior design spaces that represent crossmodal correspondences with tangible objects where emotional percepts were located mostly on the other two quadrants, i.e. negative pleasure - positive arousal and positive pleasure - negative arousal (Lin et al., 2021). Thus, there is potential to reliably elicit emotional affect across all four quadrants of the pleasure-arousal model by combining multiple types of haptic feedback. Moreover, it is key that designers carefully consider the use of vibrotactile feedback in multisensory interaction to convey congruent emotional precepts, particularly whether used as a complementary or replacement modality.

Given the ubiquity of vibrotactile capabilities of consumer devices, the design space can be used in a wide range of applications. For example, XR experiences increasingly combine visual information with haptic feedback to enhance the sense of immersion and invoke emotional responses (Pezent et al., 2019; Lopes et al., 2018). Others are creating visual-haptic content to improve mobile gaming experiences (Singhal and Schneider, 2021); however, these works did not account for crossmodal correspondences effects and could, thus, leverage our findings. In inclusive education, particularly in mixed-visual abilities settings, the design space could inform the creation of emotionally-rich multisensory learning experiences (e.g., storytelling (Antunes et al., 2022), play (Metatla et al., 2020), and computational thinking (Rocha et al., 2021)). In interpersonal and intimate communication applications that often use abstract visual feedback (Frey et al., 2018), they could convey specific emotional states, provide more engaging experiences, and manage users' attention through vibrotactile stimuli.

5.5. Limitations and future work

Our 30-participant sample mostly included young adults recruited from a local University. Although it guarantees some consistency in terms of educational background, it falls short of exploring a broader spectrum of cultural, and educational profiles. Further research can replicate the reported study with a wider demographic and account for individual differences (e.g., age, personality traits, creativity).

We acknowledge that hardware capabilities have constrained our stimuli design. Therefore, all the findings were based on the 18 stimuli available. Other vibrotactile actuators could have other characteristics, leading to different stimuli and emotional perceptions; future studies should explore how other frequencies and amplitudes map to emotions. We assessed crossmodal correspondences between vibration and emotion and between vibration and colour separately. Although we gained valuable insights into how vibrotactile stimuli affect other modalities, future research can extend this work by investigating combined effects (e.g., Wilson and Brewster (2017)). Particularly, *how* modalities are combined and whether appraisals are averaged or added across two modalities. Moreover, assessing the dominance and congruence between senses would be an interesting research avenue.

In the presented user study, we used a force-choice paradigm; i.e., we requested participants to provide emotional or colour associations for all stimuli. We expected stimuli with no clear associations to have a random-like or neutral response distribution. Results show colour associations greater than expected by chance and reliable emotional responses (either positive or negative) to specific vibrotactile stimuli. Nevertheless, future work can include a choice of 'none of the above' to allow the participants to respond when they do not feel any clear association or attempt to measure individual differences in the experience of the task by including a scale from 'I chose completely randomly' to 'This feels very right'.

Finally, we systematically investigated three vibrotactile amplitude levels and six angular frequency levels. In terms of perceived pleasure, we found that perception increases with amplitude and angular frequency; however, pleasure ratings stabilised for high frequency and high amplitude stimuli, which suggests an optimal level for vibrotactile properties that maximise the perception of pleasure. Here, our findings highlight the possible limitations to the linear predictability of crossmodal correspondences. Future work should explore the adequacy of multi-factor (i.e., amplitude, angular frequency) non-linear models to explain vibrotactile-emotion associations as well as additional levels of amplitude and angular frequency and their effect on participants' crossmodal correspondences.

6. Conclusion

We presented a systematic exploration of vibrotactile stimuli with emotional categories and colour properties. Results show statistically significant associations between vibrotactile amplitude and angular frequency with emotional dimensions of pleasure, arousal, and dominance. We also found amplitude-hue associations and a negative amplitude-brightness relationship. Moreover, we provide qualitative data on participants' association strategies, highlighting the role of vibrotactile parameters and previous lived experiences. These results extend prior work on haptic crossmodal correspondences, particularly when using vibrotactile feedback. We synthesise the findings in a design space that can aid designers in creating multisensory experiences.

CRediT authorship contribution statement

Isabel Neto: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Conceptualization. **Isabel Soares:** Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ana Paiva:** Writing – review & editing, Supervision, Funding acquisition. **Hugo Nicolau:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ijhcs.2025.103459.

Data availability

Data will be made available on request.

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