Toward Affective Handles for Tuning Vibrations

HASTI SEIFI, MATTEW CHUN, and KARON E. MACLEAN, University of British Columbia, Canada

When refining or personalizing a design, we count on being able to modify or move an element by changing its parameters rather than creating it anew in a different form or location—a standard utility in graphic and auditory authoring tools. Similarly, we need to tune vibrotactile sensations to fit new use cases, distinguish members of communicative icon sets, and personalize items. For tactile vibration display, however, we lack knowledge of the human perceptual mappings that must underlie such tools. Based on evidence that affective dimensions are a natural way to tune vibrations for practical purposes, we attempted to manipulate perception along three emotion dimensions (*agitation*, *liveliness*, and *strangeness*) using engineering parameters of hypothesized relevance. Results from two user studies show that an automatable algorithm can increase a vibration's perceived *agitation* and *liveliness* to different degrees via signal energy, while increasing its discontinuity or randomness makes it more *strange*. These continuous mappings apply across diverse base vibrations; the extent of achievable emotion change varies. These results illustrate the potential for developing vibrotactile emotion controls as efficient tuning for designers and end-users.

CCS Concepts: • **Human-centered computing → Empirical studies in HCI**;

Additional Key Words and Phrases: Affective haptics, design and personalization tools, end-user perception, emotion dimensions

ACM Reference format:
Hasti Seifi, Mattew Chun, and Karon E. Maclean. 2018. Toward Affective Handles for Tuning Vibrations. *ACM Trans. Appl. Percept.* 15, 3, Article 22 (July 2018), 23 pages.
https://doi.org/10.1145/3230645

1 INTRODUCTION

From cell phones to sensate suits, haptic technology has recently proliferated; studies routinely predict high utility for vibrotactile notifications in everyday life [4, 5, 13, 32]. Adoption, however, has been slow. Advances in hardware theoretically allow sensations beyond undifferentiated buzzes, but even professional designers struggle to express memorable, aesthetically pleasing percepts by twiddling available engineering parameters. It can take years to develop a good intuition, and this knowledge is then hard to articulate or transfer. Personal or shared libraries of examples are currently the best mechanism; new expressive effects are often the result of modifying existing repertoires [36]. This is potentially a slow process, with most time spent laboriously exploring alternatives—a barrier to creative design and the antithesis of improvisation. Perceptual controls that allow quick, direct modifications to sensations will be highly valuable in this process.

For end-users, personalization can improve utility and adoption of haptic signals [42, 47]. Consumers want to manipulate personal content more than ever [15, 17, 33]. The status quo is an immutable library, which provides

Authors' addresses: H. Seifi (corresponding author), M. Chun, and K. E. MacLean, University of British Columbia, 2366 Main Mall, Vancouver, BC, V6T1Z4 Canada; emails: {seifi, mchun345, maclean}@cs.ubc.ca.

https://doi.org/10.1145/3230645

users with a limited pre-designed set of effects to choose from. Given effective navigation, this helps; but given a choice, users have indicated preference for high-level controls that tune those predesigned effects to express a personal representation [38, 40].

In more mature domains, tools support varying levels of control and expertise. With Adobe Photoshop, one can manipulate pixel-level image features (crop, select a region, color fill) and overall perceptual attributes (brightness control, artistic filters) [30]. Adobe Lightroom provides photography enthusiasts with perceptual sliders to manipulate clarity, vibrance, saturation, and highlights, which would otherwise require manipulating individual RGB pixel values in photo regions [8]. Instagram lets any smartphone user quickly choose perceptually salient filters for more polished or customized images [12].

Manipulating vibrations brings similar needs. With existing tools, we modify *engineering* parameters: cropping part of a signal or changing its amplitude, waveform, or frequency at specific points along its timeline. With *sensory* controls, we could change perceptual attributes like roughness, speed, or discontinuity. Finally, *emotion* controls could address the mix of cognitive percepts that the vibration engenders. Here, an important question is what haptic controls would be most meaningful and useful to designers and end-users.

Past haptic studies suggest affective (emotion) dimensions to be an answer. While all three will be valuable for a professional designer, amateurs (whether a designer or an end-user) especially need the directness of emotion controls. Further, researchers have argued for the inherent neural link between touch and emotions and the memorability of affective tactile signals [10, 21, 29]. Other findings point to the effectiveness of emotions as a framework for describing and accessing tactile sensations. In navigating a large vibration library, organized by a set of schemes including emotional as well as other descriptive perspectives (such as metaphoric or usage associations), users preferred and most often used the emotion scheme to find vibrations [40]. Together, these illustrate the importance of emotional traits as a target for meaningful vibrotactile design.

Throughout this article, we use the term *parameter* to signify vibration *attributes* that can be controlled. We aim to parametrize emotion attributes for manipulation and control (i.e., emotion *controls*), using the already manipulable engineering parameters.

1.1 Research Questions, Approach, and Contributions

In this article, we investigate the possibility of emotion controls for vibrations. We began from data indicating which emotion attributes users are most sensitive to: a previous analysis of user perception of a 120-item vibration library (*VibViz*) indicated primary alignments with *agitation*, *liveliness*, and *strangeness* [39]. These became our candidate controls. For inclusion in design tools, such controls must further be automatable. This requires establishing a continuous mapping between the emotion attributes of interest and the manipulable engineering parameters of a display hardware (e.g., a C2 actuator [7]). The mapping must be consistent (or characterized) for a wide set of starting vibrations. Further, although not required for automatability, users can benefit from knowing the degree of emotion change, given a vibration's initial characteristics and the effect of adjusting one emotion control (e.g., *agitation*) on other emotion attributes (such as *liveliness* and *strangeness*).

We addressed the primary goal of automatable emotion controls through four subsidiary questions.

RQ1: What vibrotactile engineering parameters influence primary emotion attributes?
Previous work showed the influence of engineering parameters on basic emotion dimensions of pleasantness and arousal. Here, we needed similar data for more nuanced emotion attributes. We selected a manageable set of starting-point "base" vibrations that represent the diversity in possible sensations and then determined influential engineering parameters from literature and experimentally, using sensory attributes (e.g., *roughness*) as a middle step (Figure 1). We derived a set of vibrations from the base examples by modifying those influential engineering parameters and verified their impact in a study where participants rated *agitation*, *liveliness*, and *strangeness* of the vibration derivatives relative to the bases (Study 1). Towards this question, we contribute three sensory attributes that significantly impact

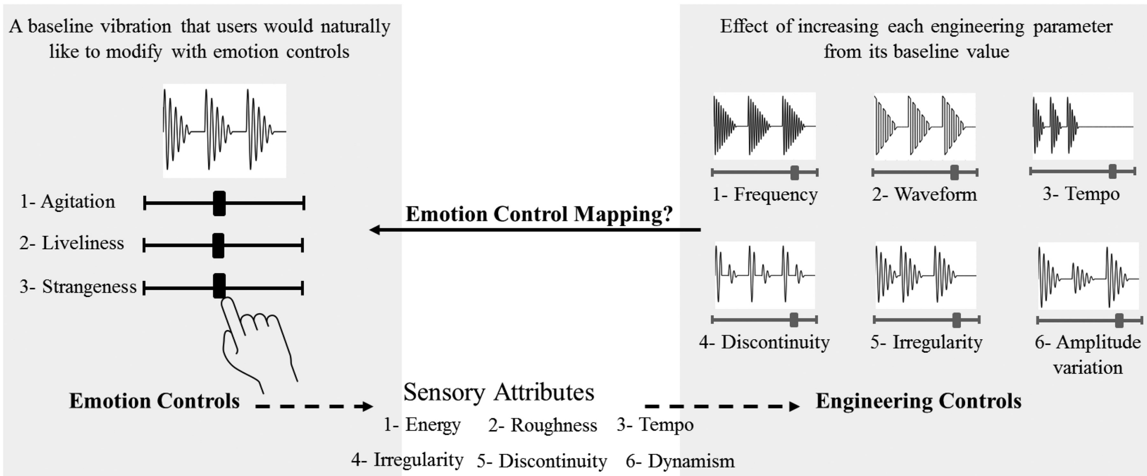


Fig. 1. Users mentally align vibrotactile sensations along several primary emotion attributes (left column). To exert direct control over these with design tools, we require a direct, automatable mapping from manipulable engineering parameters (solid line). To find this mapping, we used sensory attributes as a middle step—first establishing a link from emotion to sensory attributes and then from sensory to engineering parameters (dashed line).

perception of a vibration's three primary emotion attributes, as well as the engineering parameters that drive *them.*

RQ2: Can we alter a primary emotion attribute of a vibration (e.g., its *liveliness*) on a continuum by manipulating influential engineering parameters?
We derived new stimuli from the base vibrations using three successively more extreme applications of the influential engineering parameters from the previous step. Then, in Study 2, we examined whether these derivatives lay on a perceptual continuum between the emotion attributes and engineering parameters.

RQ3: How do characteristics of a base vibration impact a perceived change?
We examined how control effectiveness is amplified or minimized by properties present in a vibration starting point. We analyzed variations in the ratings provided in our two user studies for ten base vibrations that varied in their engineering characteristics, and showed that the mappings found for RQ2 hold for various vibration characteristics. We present qualitative descriptions of how these characteristics influence the extent of emotion change.

RQ4: How independent are these emotion dimensions?
We analyzed correlation of ratings for the three dimensions, and tested for significant effects of engineering parameters on multiple emotion dimensions. We show that our proposed *emotion-engineering* mappings are not completely orthogonal: i.e., a change in an engineering attribute can impact perception of all three emotion dimensions to varying degrees.

In tackling these questions, we contribute:

- a process for parameterizing emotion attributes for control,
- two emotion controls and their mappings to engineering parameters, and
- directions for future research and development in haptic perception and design tools.

In the rest of this article, we first review related work (Section 2) and then describe how perceptual controls can be used by designers and end-users (Section 3.1) and detail our process for identifying base vibrations and relevant vibrotactile engineering parameters (Sections 3.2 and 3.3). We detail the two user studies (Section 4) and their results (Section 5), discuss findings and three example tuning interfaces (Section 6), and then finish by outlining future avenues for research and tool design (Setion 6.4).

2 RELATED WORK

2.1 Haptic Design and Inspirations from Other Domains

Haptic designers commonly build on design guidelines or tool inspirations from more mature domains of design.

Design and personalization process: Built on existing theories of design thinking, MacLean et al. identified a set of major design activities and verified and characterized them for haptic experience design as follows: *browse*, *sketch*, *refine*, and *share* [19]. Design often starts by *browsing* existing collections to get inspiration, characterize the problem, and gather a starting set of examples. In *sketching*, designers quickly explore the design space by creating incomplete and rough sensations, making rapid changes to try alternative designs. Throughout the process, designers continuously *refine* a shrinking set of sensations to achieve a few final designs. Tweaking and precise aesthetic adjustments are the hallmarks of the refine activity. Finally, the sensations are *shared* with others to get feedback, reach target end-users, or disseminate design knowledge and contributions. In this framework, tuning controls facilitate the refinement process by expediting generation of salient alternatives for a given sensation.

Software and game personalization literature informs us about user motivations and desires. According to these, personalization increases enjoyment, self-expression, sense of control, performance, and time spent on the interface [2, 15, 22]. Ease-of-use and ease-of-comprehension in personalization tools engender take-up, while modifications are discouraged by difficulty of personalization processes [2, 18, 20, 25, 26].

Building on these, we anticipate that an efficient *tuning* mechanism would enhance users' control and enjoyment of haptic notifications and improve their adoption rates among the crowds.

Intuitive authoring and personalization tools: Similarly, haptic authoring tools frequently incorporate successful paradigms from other domains. For example, Mango, an authoring tool for spatial vibrations like a haptic seatpad, is modelled after existing animation tools [34]. Exploiting music analogies, interfaces such as the Vibrotactile Score represent vibration patterns as musical notes [16]. Our inspiration for perceptual and emotion tuning controls comes from the visual and auditory domains. In music streaming platforms such as GooglePlay music, Musicovery, and MoodFuse, users can choose to search for songs based on key terms relating to mood or scenarios such as "keeping calm and mellow" or "boosting your energy" in addition to standard music genre categories [9, 23, 24]. Similarly, photo editing software such as Adobe Lightroom or Snapseed application utilize controls named to evoke emotion attributes such as "clarity" or "drama," which adjusts several pertinent features of the image (contrast, highlights) to create an effect [8, 41]. Among audio design tools, Propellerhead's "Figure" application provides audio presets such as "80's Bass" and "Urban" as well as controls such as "weirdness" for creating and remixing music pieces [31].

These examples show the prevalence of perceptual controls for accessing and modifying stimuli in other modalities, and further highlight the gap in the haptic domain.

Stimuli design: Past research has drawn analogies between vibrotactile and audio signals to develop design guidelines and even hardware for haptics [3, 7, 11, 44].

Rhythm and pitch are important attributes of both audio and vibrotactile signals [11, 44]. Van Erp et al. designed 59 vibrations using short pieces of music while others developed crossmodal tactile and auditory icons based on common design rules [3, 11, 44]. In hardware design, voice coil actuators can take audio files as direct input and are commonly used in research for their high expressive range.

In this work, we benefit from these commonalities: we use audio editing software called Audacity and a voice coil actuator (C2 tactor) to modify and display the vibration files [1, 7]. Further, we use the definition of tempo used in audio files and report its fit for users' perception of vibration's speed [28].

2.2 Affective Vibration Design

RQ1 builds on previous research in this area. Our own past work links the three proposed emotion dimensions to vibration sensory attributes; other studies provide guidelines linking sensory attributes to engineering parameters enabling the scheme laid out in Figure 1.

VibViz library and five vibrotactile facets: In a previous work [40], we compiled five categories or facets of vibration attributes: (1) *physical* or engineering parameters of vibrations that can be objectively measured (e.g., duration, rhythm, frequency), (2) *sensory* properties (e.g., roughness), (3) *emotional* connotations (e.g., *exciting*), (4) *metaphors* that relate feel to familiar examples (e.g., *heartbeat*), and (5) *usage examples* or events where a vibration fits (e.g., *incoming message*). We designed a library of 120 vibrations for voice coil actuators (i.e., .wav files) and released a web-based interactive visualization interface (a.k.a. *VibViz*) that allows quick access to the vibrations through the five categories.

Here, we used the *VibViz* interface to choose a diverse set of basis vibrations from this library for our user studies.

Mapping engineering parameters to emotion and sensory attributes: In [39], we collected users' perception of the 120-item *VibViz* library according to the four perceptual facets of *sensory*, *emotion*, *metaphor*, and *usage example* attributes. We analyzed the ratings and tags provided to identify the underlying semantic dimensions for these four facets. Results from factor analysis and correlation of tags, situated in different facets, linked sensory attributes of the vibrations to the other three facets. We summarized the results from that analysis into (1) three emotion dimensions (agitation, liveliness, strangeness) and their correlation with (2) six sensory attributes (energy, roughness, tempo, discontinuity, irregularity, and dynamism) (Appendix A, Table 1 details these linkages).

Others linked vibration's engineering parameters to sensory attributes as well as to pleasantness and urgency [14, 35, 46, 48]. Some general trends have emerged despite hardware dependence of specific engineering parameters and their reported threshold values: a vibration's energy depends on its frequency, amplitude, duration, and waveform, and sine waveform is perceived as smoother than a square wave [27, 35]. No definition exists for changing a vibration's tempo (trivial) and discontinuity, irregularity, and dynamism. Also, past studies show that vibrations with higher energy, duration, roughness, and envelope frequency are less pleasant and more urgent [35, 46]. However, to our knowledge, these studies do not go beyond pleasantness and urgency (a.k.a. arousal) to link more nuanced emotion attributes to engineering parameters.

In this article, our objective is to develop *emotion-engineering* mappings for our three emotion attributes, thereby creating a path through which we can control these cognitive dimensions—which up to this point we have been able to perceive and analyze with but not produce at will [39, 40].

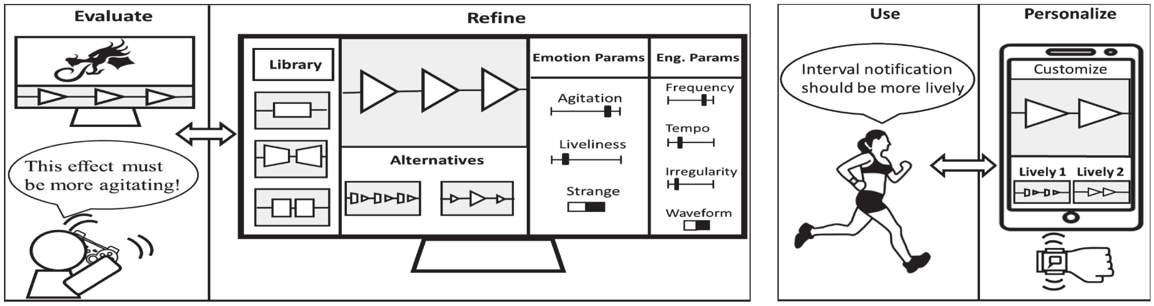
3 STARTING POINTS: USE CASES, INITIAL VIBRATIONS, AND LINKAGES

To address our research questions, we carried out three initial steps. First, we established a set of guiding use cases to frame our studies. Then, as a starting point for tuning, we chose a vibration subset from the *VibViz* library with relevant diversity. Finally, we estimated initial linkages of the emotion attributes to engineering parameters using past literature and our own pilot studies.

3.1 Design and Personalization Use Cases

In two exemplar use cases, emotion controls facilitate otherwise cumbersome design and personalization tasks.

Tuning a vibration set for a game (Figure 2(a)): Alex, a haptic designer, is developing a set of vibration effects for different scenes and interactions in a new multimodal game. While talking to stakeholders, he refines some of the sensations to be more "alien," "fun," or "agitating," trying for a distinct yet coherent sensation experience.



(a) Haptic **design** inevitably involves several rounds of evaluating sensations (left) and refining them (right). With emotion controls, designers could efficiently explore the affective design space around an example or starting point.

(b) **Personalization:** End-users untrained in haptics could efficiently personalize vibration notifications in situ, during or after use, by applying emotion filters to preset vibrations.

Fig. 2. Use cases for tuning vibrations' characteristics, using parameters aligned with users' cognition and design objectives: for both cases, controls based on emotion attributes enable "direct manipulation" from the user perspective.

He iteratively adjusts emotion and engineering controls for several vibrations in the game set, testing each alternative quickly and comparing the feel with the rest of the vibrations in the set.

Personalizing daily notifications (Figure 2(b)): Sarah often does "interval workouts"—alternating fast and slow running pace for pre-set durations. She needs clear notifications when an interval starts, or ends, both differentiable from other notifications even when she's strenuously exercising. Recently she has installed an application that lets her select the events triggering a notification on her smartwatch and associate them with vibrations from a list. She can preview and apply alternative feels for a vibration (e.g., a more *lively* version) by quickly tapping on available emotion filters.

We note that while both designers and end-users may wish to tweak a single or set of sensations, user *groups* may have different needs. We anticipate that when the latter customize sensations for their own use, they will prefer simple and quick adjustments with intuitive controls. Conversely, the former may need to achieve more polished or generalizable results and will need finer-tuned control over emotion as well as engineering controls.

3.2 Choosing Basis Vibrations

To develop an emotion control that can tune any given vibration, one needs to either study a large set of vibrations with many attributes or examine a smaller set in a systematic way. The first approach requires extensive data collection and large-scale (e.g., crowdsourced) experimental methods that are currently difficult with haptics [37]. We chose the second approach, using rhythm to structure our investigation as past research report it to be the most salient perceptual parameter for determining vibration similarity [43].

Two authors independently chose a representative subset of *VibViz* vibrations that varied in rhythmic features, and consolidated them into a 17-item set. We further narrowed these to five vibration pairs, with each pair representing a rhythm family (Figure 3), to examine consistency of the *tuning* results within and between the paired members.

3.3 Identifying Influential Engineering Parameters

In a two-step process, we first identified an emotion to sensory (*emotion-sensory*) and then a *sensory-engineering* mapping.

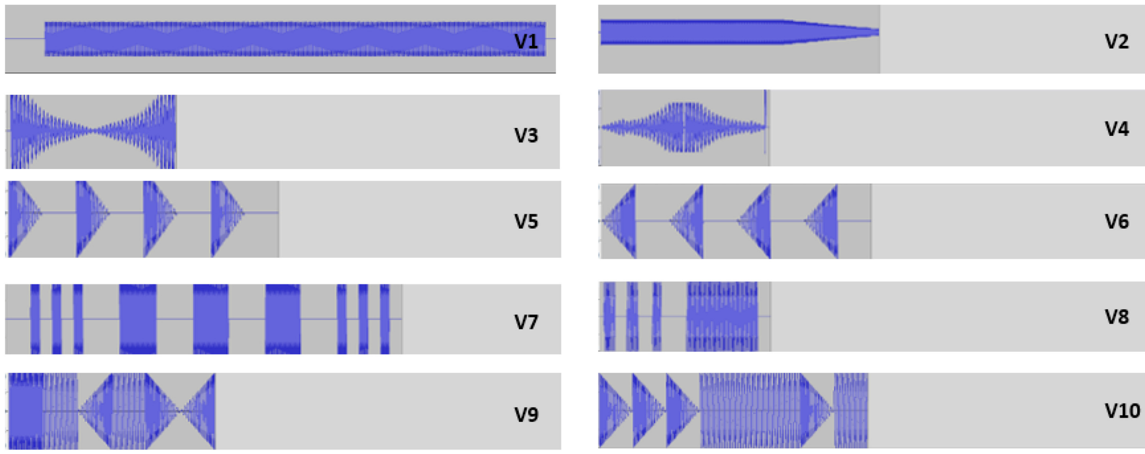


Fig. 3. Ten basis vibrations (five pairs) from the *VibViz* library, selected for our studies as tuning starting points. Each row represents a vibration pair that shares unique rhythm and envelope attributes not found in other pairs. As an example, V9 and V10 both have several connected pulses with various envelopes (constant, rampup, or rampdown).

Emotion-sensory mapping: In a previous work, we identified sensory attributes correlated with each emotion attribute [39]; see See Appendix A, Table 1 for a summary. Based on those results, we selected six attributes for further investigation: energy, roughness, tempo, discontinuity, irregularity, and dynamism.

Sensory-engineering mapping: We derived relevant engineering parameters for energy and roughness from the literature but did not find prior work defining tempo, discontinuity, irregularity, and dynamism. For these, we manually and iteratively altered our initial 17 vibration *.wav* files using the Audacity audio editing tool [1], testing candidates in small pilots. We tested various applications of these sensory attributes until we converged at six potentially influential engineering parameters (frequency, waveform, tempo, discontinuity, irregularity, and amplitude variation) for further investigation in user evaluations (See Appendix B, Table 2 for more details on our sensory to engineering mappings).

4 USER STUDIES

Having identified a set of potentially influential engineering parameters, we sought continuous mappings from them to emotion attributes for a given base vibration (RQ1-4). Here, we followed an exploratory research process involving a pilot and two user studies, with each study informing the parameters and study design for the next one. In all of the studies, participants rated stimuli derived from a base vibration, on *agitation*, *liveliness*, and *strangeness*. In Study 1, we verified that a mapping existed between the emotion and engineering parameters noted in Section 3.3 and in Study 2 we tackled the mappings' continuous nature.

4.1 Overview of the User Studies

Pilot Study: We established our study protocol in a pilot study with 10 participants, where we studied six derivatives for each base, designed by modifying one of the six engineering parameters identified in Section 3.3 (frequency, waveform, tempo, discontinuity, irregularity, and amplitude variation). Results indicated two top-performing engineering parameters for each dimension: for *agitation*, waveform and frequency; *liveliness*, waveform and tempo; and *strangeness*, discontinuity and irregularity.

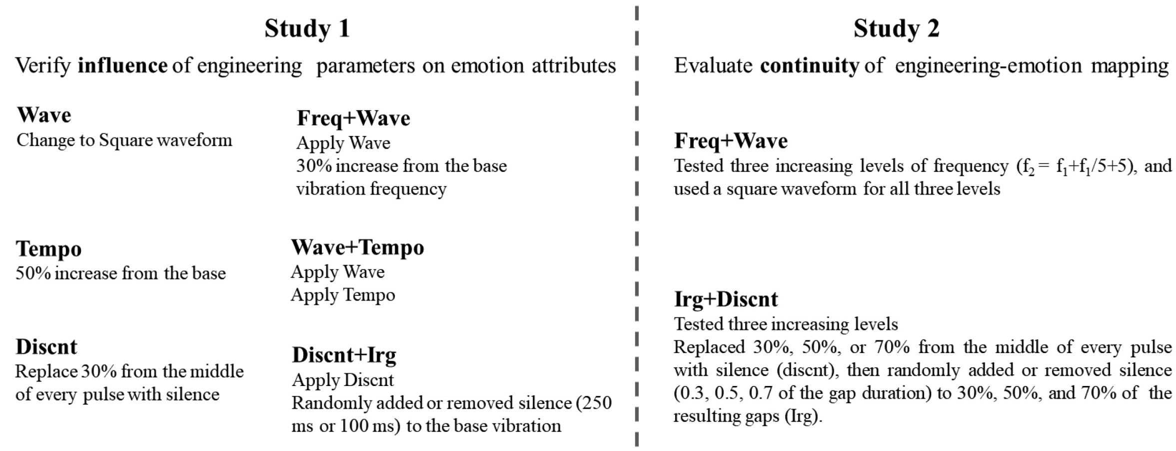


Fig. 4. Overview of the engineering parameters and evolution of their functional implementation to achieve control over the three emotion attributes in Studies 1 and 2. Values listed under each engineering parameter indicate changes applied to the base vibrations in the associated study. “Freq,” “wave,” “discnt,” and “irg” denote frequency, waveform, discontinuity, and irregularity, respectively.

Study 1—Verifying influence of engineering parameters on emotion attributes: We examined the effect of the top-performing engineering parameters on the emotion attribute in a formal user study and explored whether one can achieve a more pronounced emotional effect by applying changes to both top-performing parameters.

Study 2—Evaluating continuity of engineering-emotion mapping: The next step was to establish continuity in a mapping from engineering parameters to emotion attributes (RQ2) by examining the impact of successively more extreme applications of the engineering parameter combinations that were found to be influential in Study 1, namely frequency+waveform and irregularity+discontinuity. We investigated the effect of an increase in frequency+waveform and irregularity+discontinuity on *agitation*, *liveliness*, and *strangeness*.

4.2 Methods

Studies 1 and 2 (as well as the pilot) shared apparatus and procedure. The studies differed in stimuli set and size. Both studies were approved by the ethics review board at the University of British Columbia.

Stimuli

Study 1: We utilized all 10 base vibrations (5 pairs), creating eight derivatives for each as follows: (a) the base vibration itself, as a statistical control; (b) six derivatives per base, representing change in waveform, tempo, discontinuity, frequency+waveform, waveform+tempo, and irregularity+discontinuity (see Figures 4 and 5); and (c) a randomly chosen duplicate of one of these seven to assess rating reliability. This resulted in a total of 90 vibrations (10 base and 80 derivatives) rated in comparison to the base vibrations by each participant, i.e., 80 comparisons.

Study 2: We included eight derivatives for each of the 10 base vibrations: (a) the base vibration itself, (b) three levels of frequency+waveform, (c) three levels of irregularity+discontinuity, and (d) a randomly chosen duplicate of one of these seven. As for Study 1, this resulted in 90 vibrations (10 base, 80 derivatives) rated by each participant—80 comparisons.

For the frequency+waveform derivatives, the frequency increase at each level was based on the Weber’s JND law ($f_2 = f_1 + \frac{f_1}{5} + 5$). Waveform did not change across the three levels. For the irregularity+discontinuity

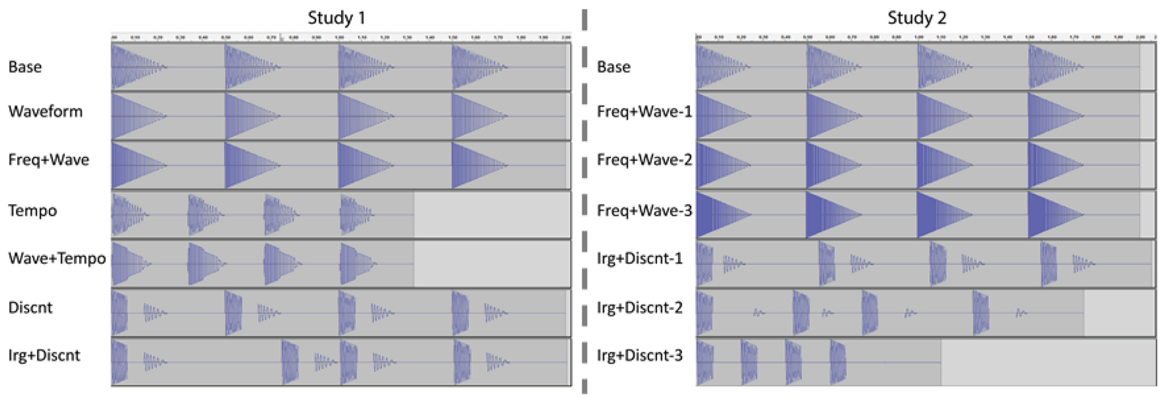


Fig. 5. An example of vibration derivatives in Studies 1 and 2 (designed for base vibration V5). Increasing frequency is represented through increased image color saturation. Increasing tempo (i.e., rhythmic rate) resulted in shorter signals as a side effect. Discontinuity and irregularity+discontinuity are implemented by adding silent periods (represented as zero amplitude), and by varying the duration of these silent periods.

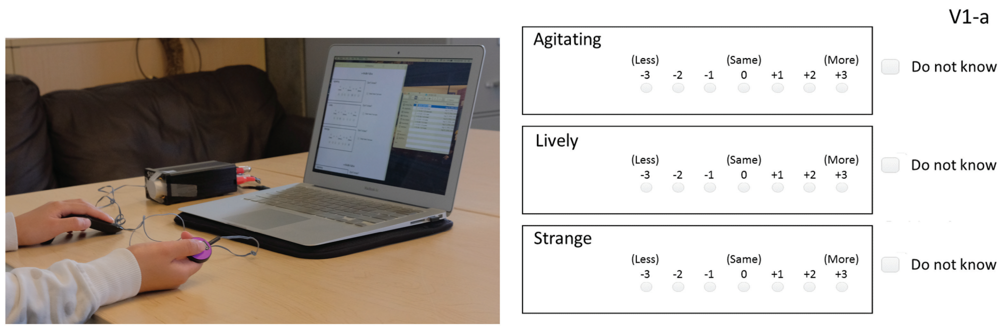
derivatives, we first applied discontinuity by removing 30%, 50%, and 70% from the middle of each pulse in the vibration. To systematically vary irregularity, we then randomly added or removed silence from the first 30%, 50%, or 70% of the resulting gaps, with the amount of silence proportional to the duration of the gap (30%, 50%, and 70% of the gap duration, respectively, which translated to values between 0 and 0.4ms, Figure 4).

Participants: We recruited 20 (12 females, 18 native English speakers) and 22 (15 female, 19 English) participants for Studies 1 and 2, respectively, by advertising on a North American university campus ($15 compensation for a 1-hour session). Individuals could only attend one of the two user studies. Participants reported no exposure to haptic signals other than vibration buzzes on their cellphones. Studies 1 and 2 lasted an average of 35 and 45 minutes, respectively.

Apparatus: To display the vibrations, we used a C2 tactor, connected to an amplifier and a laptop. Each base vibration and its derivatives were placed in a separate desktop folder visible on the laptop screen. The rating interface was an online questionnaire with each page representing all the derivatives and required ratings for one of the base vibrations (randomized order). Each question on a page displayed the name of the derivative (e.g., V1-a) and three Likert item ratings (−3 to +3) for *agitation*, *liveliness*, and *strangeness* (Figure 6(b)). A rating of −3 indicated that a derivative had considerably less of an emotion attribute compared to the base (i.e., less agitating or negative influence of the engineering parameter), while +3 indicated having more of the emotion attribute (i.e., more agitating or positive influence). Participants played the vibration files on the laptop, provided their ratings on the survey, and listened to pink noise through headphones to mask any sound from the actuator.

Procedure: Study sessions were held in a private, closed-door room and started with a short interview. After asking for the participant's demographics, the experimenter asked them to imagine and define an *agitating*, *lively*, or *strange* vibration using their own free-form words and typed their responses on a computer. To calibrate on common definitions, the experimenter then provided a verbal definition of the three emotion terms with short lists of adjectives drawn from emotion synonyms in Reference [39] and asked them to use these synonyms in the remainder of the study:

- *lively:* happy, energetic, interesting
- *agitating:* annoying, urgent, angry, uncomfortable
- *strange:* odd, unfamiliar, unexpected



(a) Apparatus for user studies.

(b) Rating interface showing one vibration derivative and three Likert item ratings representing the three emotion attributes.

Fig. 6. Experimental setup for the pilot and Studies 1 and 2. The rating interface shown in (b) appears on the computer screen in (a).

The experimenter described these synonyms again whenever the participants asked for them but in most cases, these synonyms were well aligned with the participants' initial descriptions for the emotion attributes (see Appendix C, Table 3). The rating task consisted of feeling all the derivatives for a base vibration first and then providing three ratings for each derivative to indicate whether it was more/less *agitating*, *lively*, and *strange* than the base vibration or to mark a rating with "do not know." Participants held the tactor between the tip of the fingers (Figure 6) and rated each derivative once (randomly ordered) while having access to its base vibration as well as all other derivatives in that set (placed in a folder on the experimenter's laptop) throughout the experiment. In a post-interview, the experimenter asked for and recorded participants' definition of the three emotion terms to identify any changes in the emotion definitions as a result of feeling the vibrations. At the end, the experimenter addressed any questions about the study such as its potential use cases and the engineering parameters used in the experiment.

4.3 Analysis

Replaced Values: Of over 10,000 ratings collected, we received a small number (five in Study 1, six in Study 2) of "do not know" responses. We replaced these with the median of the other ratings for the corresponding derivative.

Duplicate Trials: The median of rating differences between a derivative and its duplicate (inserted to estimate reliability—see Section 4.2) was 0 and 0.5 (7-point scale) in Studies 1 and 2, respectively. We therefore removed ratings for the duplicate derivatives for the rest of our analysis.

Nonparametric Factorial Analysis (ART): We then performed a full factorial analysis to test for the effects of the engineering parameters. Because this involved multiple nonparametric factors, we used the Aligned Rank Transform (ART) for nonparametric factorial analyses [45]. ART was designed for and has been used by many as a multifactor nonparametric alternative for ANOVA. It applies a rank transformation on the rating data [6] and then runs an ANOVA test on the ranks. Thus, results from ART are interpreted similarly to the ANOVA results. For each study, we ran the test on the ratings for *agitation*, *liveliness*, and *strangeness* separately, using two factors of engineering parameter (7 levels) and base vibration (10 levels). Since ART is an omnibus test, we used Tukey's posthoc analysis with corrected p-values for multiple comparisons with an alpha level of 0.05.

5 RESULTS

We first present qualitative descriptions collected in the pre and post interviews, then show minimally processed rating data, and present our ART analysis with respect to our research questions (RQ1–4).

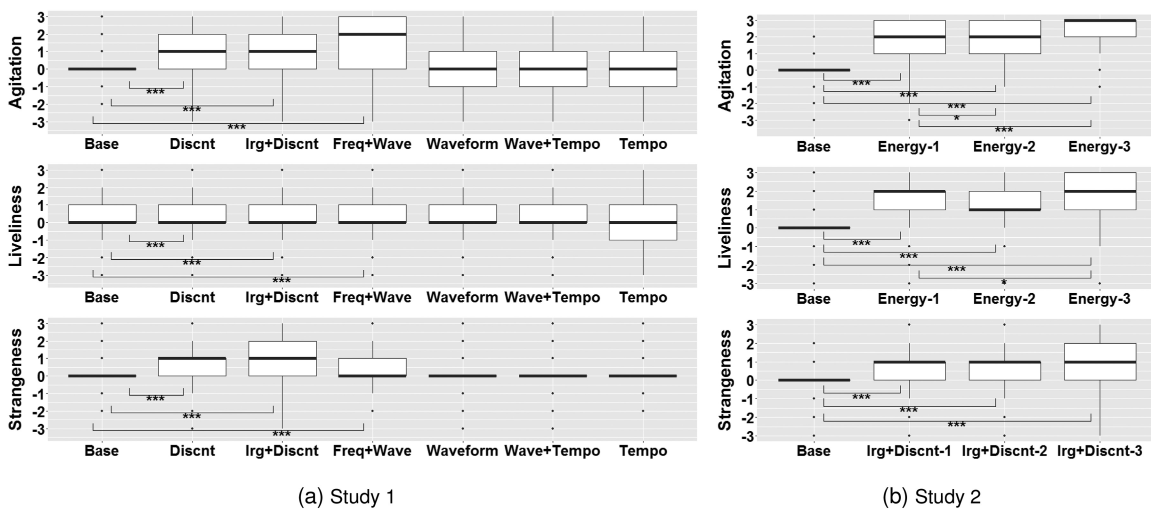


Fig. 7. Boxplot of *agitation*, *liveliness*, and *strangeness* ratings for the base vibration and vibrotactile derivatives representing changes in the engineering parameters in Studies 1 and 2. Starred lines mark significantly different pairs of conditions, with *** and * indicating significant results at $p < 0.0001$ and $p < 0.05$, respectively. "Freq+Wave," "Wave+Tempo," "Discnt," and "Irg+Discnt" denote frequency+waveform, waveform+tempo, discontinuity, and irregularity+discontinuity, respectively.

5.1 Verbal Descriptions for Emotion Attributes

We aggregated the emotion descriptions collected from the participants in the semi-structured pre- and post-session interviews for Studies 1 and 2 as follows. We extracted adjectives (e.g., irritating) and noun phrases (e.g., short pulses), consolidated synonyms (e.g., fast and agile), and counted total usage instances for each adjective across the participants. For example, we coded the Study 2 definition of a *lively* vibration by P18 ("more intense and faster vibrations") as strong (+1) and fast (+1) and then summed with similar adjectives from other participants (see Appendix C).

For all three emotion attributes, in the pre-interview participants mostly used descriptive emotion words when we asked them to define these concepts as they might be expressed as vibrations, in their own words. Given the same question in the post-interview, they generally drew on sensory definitions such as vibration structure and feel.

The pre-interview produced several patterns. Both *agitating* and *strange* vibrations (considered in the abstract) were labelled with adjectives typically considered unpleasant and negative (e.g., unexpected and unfamiliar for *strange* vibrations, irritating and nervous for *agitating* ones). In contrast, *liveliness* was associated with positive attributes such as energetic, happy, and pleasant.

In the post-interview, sensory definitions for *agitation* overlapped in content with both *liveliness* and *strangeness*, but the latter two did not share any descriptions (per participant or when aggregated). Specifically, *agitating* or *lively* vibrations were both described to be strong and fast, but they differed in other ways: *liveliness* was linked to short pulses and a rhythmic pattern while long, non-rhythmic, and irregular vibrations were considered *agitating*. *Strange* vibrations shared part of the *agitation* space, being likewise described as irregular and off-rhythm.

5.2 Ratings

We collected a total of 10,080 emotion attribute ratings for Studies 1 and 2 vibration derivatives. Figure 7 shows these as boxplots for *agitation*, *liveliness*, and *strangeness*.

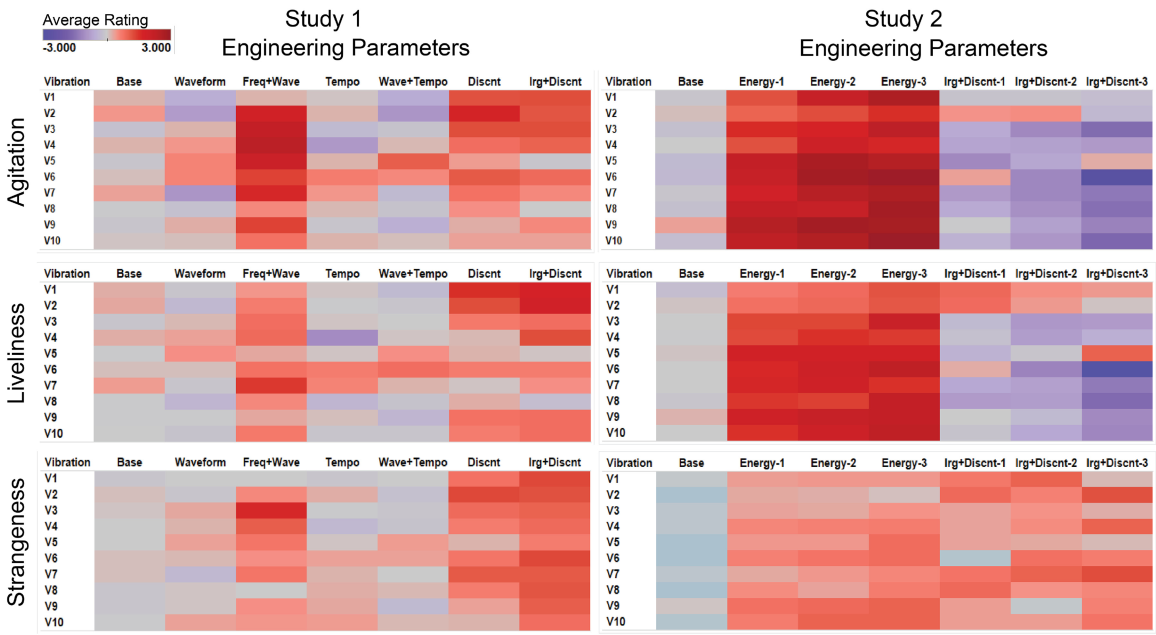


Fig. 8. Average ratings of the emotion attributes in response to variation of engineering parameter combinations (subfigure columns) for the 10 base vibrations (subfigure rows) in Studies 1 and 2. Influence of the engineering parameters on the base vibrations for that emotion attribute is denoted by color: blue is negative (bounded by average rating of −3.0, intense blue), gray is neutral (0), and red shows a positive influence (bounded at +3.0). Column saturation thus indicates strong *influence* (positive or negative) of an engineering parameter, whereas row saturation indicates *susceptibility* of that vibration to being influenced. Consistent color and saturation in a column indicates a consistent perception regardless of the base vibration; color variation suggests dependency on the base vibration.

To denote patterns of the ratings pertaining to all 10 base vibrations and 7 engineering parameters, we then visualized average ratings for each vibration derivative (Figure 8). Average ratings of −3, 0, and +3 indicate negative, zero, and positive influence of an emotion attribute on the derivative compared to the base vibration.

5.3 RQ1: Impact of Engineering Parameters on Emotion Attributes (Study 1)

The first research question's objective was to establish which engineering parameters (which we are able to manipulate) can influence perception of emotion attributes. ART analysis (Section 4.3) of our Study 1 data showed a significant main effect of engineering parameter and a main effect of base vibration on the ratings for all three emotion attributes. A posthoc Tukey's test determined which engineering parameters were significantly different from the base.

Figures 7 and 8 illustrate the outcomes. Specifically, applying frequency+waveform, discontinuity, or irregularity+discontinuity to the base vibrations resulted in a statistically significant increase in all three emotion dimensions while applying waveform, tempo, or waveform+tempo had minimal impact on the perceived emotions.

In Figure 8, the columns representing no statistical significance (waveform, tempo, and waveform+tempo) show either low emotion change (gray or low saturation cells) or inconsistent change for different base vibrations (color variations). In contrast, the majority of cells for the statistically significant parameters (the frequency+ waveform, discontinuity, and irregularity+discontinuity columns) show high emotion influence (highly saturated cells). Further, frequency+waveform resulted in the most consistent perception for *agitation* and *liveliness* while irregularity+discontinuity led to consistent results for *strangeness*.

In summary, Study 1 succeeded in highlighting possible control paths towards all three emotion attributes. Notably, the *agitation* and *liveliness* attributes shared the same engineering parameters in these results. We further investigate an overlap in their continuous mappings in Study 2.

5.4 RQ2: Evidence of Continuity of the Engineering-Emotion Mappings (Study 2)

In Study 2, we investigated mapping continuity, using three successively more extreme applications of the influential engineering parameter combinations to create the vibration derivatives.

Frequency+waveform

In analyzing the stimuli for Study 2, we noted that the three increasing levels of frequency+waveform resulted in very different actuator output energy (actuator acceleration measured as m/s^2) depending on the actuator's frequency response curve (peak at $f = 275$Hz) and a base vibration's frequency. Thus, in our analysis, we ordered the vibration derivatives used in Study 2 according to the frequency of the tactor's peak response to dictate three increasing energy values. That is, the energy sequence of $[base, energy_1, energy_2, energy_3]$ simply swapped the order of the second and third frequency+waveform derivatives: $[f_0 = 200\text{Hz}, f_1 = 245\text{Hz}, f_3 = 352\text{Hz}, f_2 = 289\text{Hz}]$.

Running ART and Tukey's posthoc on the energy-ordered data showed a significant effect of energy on all three emotion attributes. Specifically, for *agitation* ratings, this resulted in significant differences between all three energy levels (borderline significance for the revised $energy_1$ and $energy_2$, $p = 0.1$). For *liveliness*, Tukey's posthoc showed a borderline difference between $energy_1$ and $energy_3$, $p = 0.08$. For *strangeness*, the test resulted in significant differences between the derivatives and the base, with no difference between three successive energy derivatives.

Figure 8's visualization is consistent with these results. *Agitation* and *liveliness* cells show an increase in emotion change (higher saturation) for higher energy levels. We note, however, that *liveliness* cells are less saturated than the *agitation* ones for the same derivative, suggesting that these energy changes impacted *liveliness* less than *agitation*. *Strangeness* cells show an increase in saturation for three all energy levels but the effect is smaller and less consistent than the ones for *agitation* and *liveliness*.

Irregularity+discontinuity

ART showed significant main effects of the irregularity+discontinuity for all three emotion attributes. For *agitation* and *liveliness* ratings, Tukey's posthoc resulted in significantly lower ratings for all three successive energy levels (borderline significance for the $Irg + discnt_2$ and $Irg + discnt_3$ in *liveliness* ratings, $p = 0.1$). For the *strangeness* ratings, the three levels of irregularity+discontinuity were significantly different from the base but not different from each other.

5.5 RQ3: Impact of Base Vibrations on Emotion Attribute Ratings

Our ART analysis suggested that the base vibrations varied in their emotion change after applying the engineering parameters—a significant main effect of base vibration in both studies. Figure 8 depicts differences in the emotion ratings for the 10 base vibrations.

Agitation and liveliness: For all the base vibrations in both studies, applying some level of frequency+ waveform (or *energy*) tended to increase their perceived *agitation* and *liveliness* (gray to red colors). However, the extent of increase varied for different base vibrations. These differences are more pronounced in Study 1 results but are resolved after the energy re-ordering in Study 2.

To see if a vibration's base rhythm contributed to the ratings, we examined consistency of the ratings for the paired vibrations (Section 3.3) but only found one notable instance. V1 and V2, paired for being continuous and flat, received lower *liveliness* ratings that the other vibrations even with the Study 2 energy reordering.

Strangeness: All the base vibrations became more *strange* after applying irregularity+discontinuity and discontinuity. However, in some cases, the boost was minimal (low saturation cells). In Study 2, some base vibrations showed a consistent albeit gradual increase in *strangeness* (e.g., V4 and V7), but the majority did not. This is consistent with the statistical results (significant main effect but no pairwise significance) in Section 5.4. Examining the paired vibrations did not yield any apparent link between the *strangeness* ratings and rhythm patterns of the base vibrations.

5.6 RQ4: Orthogonality of Emotion Dimensions

Correlation among the three emotion dimensions: A Spearman's rank correlation test was positive for *agitation* and *liveliness* ratings (strong for Study 2 ($r = 0.67$), and weak in Study 1 ($r = 0.39$)). For Study 1, Spearman's test also revealed a moderate correlation between *agitation* and *strangeness* ($r = 0.44$).

ART results: According to the RQ1-2 results, frequency+waveform and irregularity+discontinuity impacted all three emotion attributes; however, their effect was more prominent for some emotion attributes than for others. While *agitation* and *liveliness* consistently increased with energy in both studies, the effect of irregularity+discontinuity was not consistent: These parameters tended to significantly increase *agitation* and *liveliness* ratings in Study 1 but significantly decreased them in Study 2. In both studies, *strangeness* ratings were increased by applying irregularity+discontinuity and frequency+waveform, with the impact of irregularity+discontinuity being stronger.

6 DISCUSSION

After a summary of our findings, we discuss automatability of the emotion controls given these results and reflect on our study approach and, finally, present three example interfaces supporting our design and personalization use cases.

6.1 Findings

Evidence of mapping from engineering parameters to emotion attributes (RQ1 and RQ2): We found a set of engineering parameters that can increase perception of *agitation*, *liveliness*, and *strangeness* for a given vibration. Specifically, our results suggest a linear relationship among *agitation*, *liveliness*, and the actuator's output energy. Adding irregularity and discontinuity to a vibration increases its *strangeness* but the effect does not increase with the degree of discontinuity and irregularity.

Differences observed for the base vibrations (RQ3): The extent of emotion boost depends on the characteristics of the base vibration. We found that differences in *agitation* and *liveliness* boosting were best described by the actuator's output energy, as evinced by the improved monotonicity of relationship in Study 2 versus Study 1. Rhythm and envelope played a secondary role for *liveliness*, where continuous and flat base vibrations (V1, V2) received a lower boost than did the other bases for a similar increase in energy. V7, with a symmetric rhythm of short and long pulses, was among the most lively vibrations for different energy levels.

Strangeness ratings were mixed. This may have been due to using random values in our irregularity derivatives: Sometimes this produced a regular rhythm (e.g., irg+discnt-3 for V1) and elsewhere noticeably irregular beats.

Orthogonality of the emotion controls (RQ4): Our results suggest two relatively independent emotion controls for vibrations: one that modifies *agitation* and *liveliness* jointly and another one for *strangeness*. Our results also suggest a subtle distinction between *agitation* and *liveliness* (e.g., impact of base rhythm and qualitative descriptions), which need further examination. Finally, we saw that a change in one emotion attribute can influence perception of others.

We next discuss potential automatability of emotion controls, given these results.

6.2 Automatable Emotion Controls and Study Approach

Our studies show that at least one automatable solution exists. Since our goal was to verify the existence of at least one mapping, we chose the most promising sensory to engineering mappings based on the literature and our pilots (Section 3.3) instead of doing an exhaustive search of the sensory and engineering parameter spaces in formal user studies. The results confirmed the viability of our proposed mapping for a diverse set of base vibrations. The mapping, however, is neither orthogonal nor uniform. The extent of change along the emotion dimension can vary for different vibrations, and moving a vibration along one emotion dimension can impact its other emotion attributes. These qualities are not surprising; they exist in other domains and do not undermine the effectiveness of the controls. As an example, in Adobe Lightroom, increasing the “shadows” does not change every photo to the same degree. Further, the effect of adjusting “shadows” on a photo’s “vibrance” is not always predictable.

We used a top-down approach in designing the emotion controls. We started with a set of emotion attributes, then devised a mapping to the engineering parameters. A bottom-up approach would have required developing a set of engineering controls; then building higher level controls based on emerging usage trends over time. This would have necessitated long-term usage or access to crowds to aggregate usage patterns, and the resulting controls may require background knowledge (e.g., “highlights” vs. “whites” sliders in Adobe Lightroom). Given a lack of access to the crowds [37] or a large established haptic design community, we chose the top-down approach to find an existence proof rather than an optimized solution. This process is not the only possible way, nor are these mappings necessarily unique. Over time, we anticipate that triangulation of different approaches will lead to the best results.

Exposure to vibrations led to more concrete descriptions for the emotion terms that in turn highlighted next steps for the engineering-emotion mappings. We relied on qualitative descriptions to gain perspective on practical significance of our quantitative results. Interestingly, participants became more articulate after a relatively short exposure to the vibrations. At the start, they described the three emotion dimensions mostly with other emotion words but in the post-interview, they commonly referred to the sensory and engineering parameters of the vibrations (e.g., strong, frequent pulses). In most cases, the participants’ definitions were consistent with their ratings and our hypothesized engineering parameters. In one exception, *lively* vibrations were commonly described as “fast” but tempo and waveform+tempo were not effective. We increased tempo based on the definition available for audio tracks because of the perceptual and design commonalities between the vibrotactile and auditory modalities. But our results suggest that this definition is not aligned with users’ perception and calls for a more effective model for the perception of speed in vibrations.

6.3 What Do These Results Enable? Revisiting Our Use Cases

Our motivation for this research was to empower the creation of haptic design and personalization tools. Here, we discuss three interface concepts, informed by our results, as a vehicle to relate our findings back to the design and personalization scenarios in Section 3.1 and reflect on their underlying parameters.

Vibration Instagram: Our personalization use case in Section 3.1 calls for a simple interface where ordinary users can apply a set of predefined effects to a given vibration (chosen from default vibrations on their phone or sketched with a simple tool (Figure 9)). All the effects use the same binary control and must be perceptually salient but may not rely on pre-defined emotional connotations. Users have no access to underlying engineering parameters.

Grounded in our results, one can create at least two emotionally meaningful filters (*agitating*/*lively* and *strange* effects) and several other filters representing alternative applications of an engineering parameter (e.g., different levels of irregularity+discontinuity for distinct *strange* sensations).

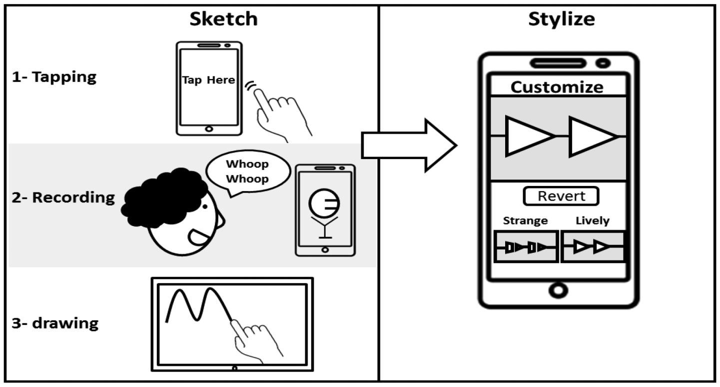


Fig. 9. Instagram for vibrations. Users would sketch a new vibration through a simple interface (e.g., by tapping on the phone screen, recording their voice, drawing a rhythm, etc. (left)) and then stylize it by applying emotion filters (right).

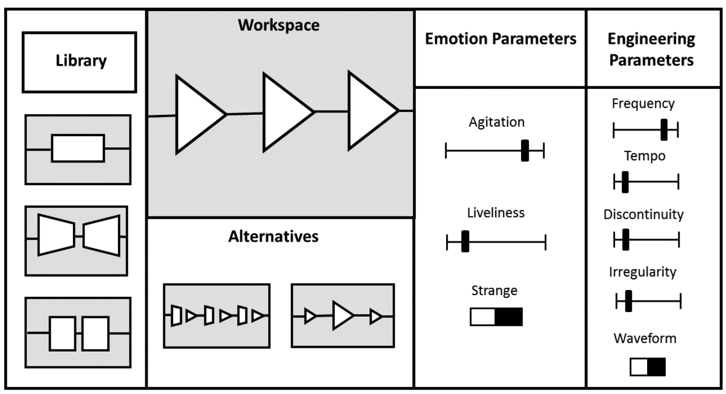


Fig. 10. Emotion toolbox. Designers would be able to start from a vibration in their library (left panel), use high-level emotion controls (third panel), and override default engineering presets as needed (right panel). Promising candidate would be saved to the bottom alternatives panel.

Emotion Toolbox: In our design use case (Section 3.1), Alex could benefit from an add-on toolbox to his vibrotactile authoring tool(s) that provides full access to the available emotion controls (e.g., switch or a slider denoting the binary or continuous nature of the possible emotion change) and their underlying engineering parameters. Ideally, the interface will allow designers to define new proprietary controls and map them to the engineering parameters.

Grounded in our results, we can now create a toolbox with slider controls for *agitation*, *liveliness*, and a switch control for *strangeness* (Figure 10). In a "details" layer, designers can see default engineering settings for each control, change the preset values for the controls, and access other engineering controls not used in current attribute definitions.

Vibrotactile Palette Generator: In designing vibration derivatives for our studies, we noticed several cases where seeing a *palette* of vibrations, each of which are perceptually distinct from the others but share a common theme, would be useful for personalization and design. For example, an end-user may wish to create a homogeneous set of wakeup alarms with increasing *agitation* for each snooze round. These cases benefit from

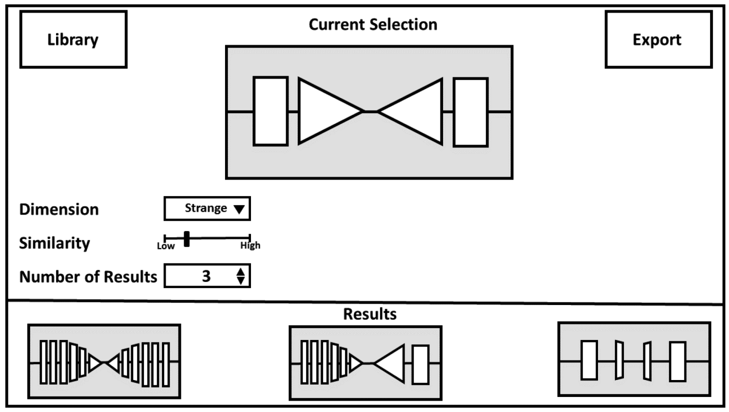


Fig. 11. Vibrotactile palette generator. Users would select a base vibration (from a library) and determine the emotion dimension for derivatives, their similarity, and number of derivatives. The system would automatically create the derivatives on demand based on a predefined algorithm(s).

an interface that can automatically generate a set of derivatives based on an input vibration along a predetermined emotion dimension (Figure 11). Users would have access to one type of multi-level discrete control for all the emotion dimensions, denoted by meaningful emotion labels to guide derivative generation, and subsequent control over semantic parameters of the underlying algorithm (e.g., number and similarity of the derivatives).

This interface concept would exploit our findings in the form of a palette generator along the *agitation/liveliness* dimension and another along the *strangeness*) dimension and vary energy and irregularity+discontinuity to derive perceptually distinct sensations with predictable emotion impact. Although applicable to both dimensions, this interface is mostly appropriate for emotion attributes such as *strangeness* which has known engineering parameter(s) but no linear effect of the parameter.

Reflections on supporting tuning scenarios: Our use cases in Section 3.1 vary in two parameters: (1) target users (designers vs. naive users) and (2) tuning task (tweaking a single vs. a set of sensations). We can now use these interface concepts as a basis for discussing how tuning scenarios, varying on these two parameters, may be supported through interface design choices.

Target Users: Ease-of-use and design control are typical interface properties of interest to both of the demographics we have identified—designers and end-users [38]. Our results indicate feasibility of achieving balances for these two properties and suggest ways they might be embodied. Specifically, Vibration Instagram limits vibration alternatives and control (fixed binary presets) to achieve simplicity and efficiency of use and thus lends itself to users who may have less design knowledge or willingness to tackle a learning curve. In contrast, Emotion Toolkit emphasizes flexibility and control for designers who may find its power and subtlety a worthwhile tradeoff for complexity, as with users of other expert tools. Finally, Vibrotactile Palette Generator provides a middle ground through semantic control over the underlying algorithm, making it suitable for both designers or tech-savvy end-users.

Vibration Tuning Task: In modifying sensations, users may wish to tweak a single item or a set of them. Our proposed interfaces support one or both of these workflows—another factor in what might suit them for a particular demographic or context. Vibration Instagram allows tuning just one sensation at a time, while Vibrotactile Palette Generator's purpose is to facilitate creating sets of related sensations. Emotion Toolkit supports both tasks; the designer can tweak a single vibration with the sliders but can also access and/or save to the vibration set using the library and alternatives panels.

6.4 Future Work

There are several avenues for extending our work. First, our results mostly reflect North American perception of emotions; verifying and extending these mappings for other cultures is an open area for future research. Second, to manage scope, we focused on the mappings that increase perception of the three emotion attributes, leaving investigation of the effect in the opposite direction (decreasing emotion percept) to future studies. Third, modelling the mappings we identified between engineering parameters and the three emotion dimensions using regression and other statistical techniques would be a critical step for automating the operation of emotion controls.

Fourth, we did not study utility of these controls for designers. Thus, to complement tool development efforts, future studies can examine these controls in situ and define relevant evaluation metrics.

We close by pointing to other conceptual approaches for moving a vibration in the emotion space that can complement and/or extend our work. Conceptually, our controls enable *extrapolation*; they start from one existing sensation and generate a new one based on a set of rules. Other frameworks should also be considered. For example,

Navigation: The system recommends alternative (but existing) vibrations from a library that have the desired emotion attribute(s) (e.g., are more *lively*) but otherwise share structure and engineering parameters with the base vibration. The user "navigates" to the alternative vibrations in the library, guided by the system recommendations.

Interpolation: The system creates a new vibration in between a starting base vibration and another with the desired emotion attributes. To make a vibration more *lively*, for example, it would interpolate between the base and a *lively* vibration. The interpolation ends could be specified by the user or automatically selected from a library.

These approaches pose different challenges and opportunities. Once applied in a design tool, they can complement one other to provide a rich toolset for designers or a seamless personalization mechanism for end-users.

7 CONCLUSION

Inspired by existing authoring tools in visual and auditory domains, our work calls for designing emotion and perceptual controls for haptics and takes a critical step towards parameterizing the emotion attributes for control and design. In particular, we present our process for tackling many challenges that are specific to automatable emotion controls, namely, establishing continuous mappings along specific emotion attributes, identifying consistent effects across various base vibrations, and finding orthogonal or consistent effects across the emotion attributes.

Through user study results, we show that emotion controls can be created automatically and propose a mapping from these proposed emotion attributes of *agitation*, *liveliness*, and *strangeness* to already-controllable vibration engineering parameters that emotion controls could traverse. For designers and application developers, our results provide two automatable mappings and highlight their potential crosstalk.

Finally, we present three example tuning interfaces and motivate future directions for research in haptic perception: (1) characterizing sensory parameters of vibrations (e.g., discontinuity, tempo) for tool development and (2) validating and refining our mappings in lab-based perceptual studies or in situ design-driven case studies.

Our results enable new interfaces for vibrotactile design and personalization, which in turn pave the way towards more expressive vibrotactile sensations and improved adoption and engagement by end-users.

APPENDIX

A LINKAGES BETWEEN THREE EMOTION DIMENSIONS AND SENSORY ATTRIBUTES OF VIBRATIONS

Table 1. Three emotion Attributes (Rows) and Their Linkages to Sensory Attributes and Tags of Vibrations, Summarized from Previous Work [39]

Emotion Attribute	Sensory Attribute (factor loading value)	Tags with High Correlation (correlation coefficient)	Tags with Low Correlation (correlation coefficient)
Agitation	Energy (.9)†	Rough (.7)	Soft (.0)
	Roughness (.8)†	Discontinuous (.5)	Smooth (.0)
	Tempo (.4)†	Dynamic (.4)†	Flat (.0)
	Complexity (.5)	Complex (.4)	Simple (.0)
Liveliness	Tempo (.5)†	Discontinuous (.6)	Continuous (.0)
	Continuity (-.4)†	Bumpy (.5)	Pointy (.0)
	Duration (-.5)	Dynamic (.4)†	Flat (.0)
			Ramp down (.0)
Strangeness	Complexity (.6)	Irregular (.5)†	Regular (.1)
	Continuity (.3)†	Dynamic (.4)†	Flat (.0)
		Complex (.4)	Simple (.2)

The second column, extracted from a factor analysis in that work, presents the sensory attributes that contribute to the same semantic constructs (a.k.a factors) as the emotion attributes. The last two columns show the most and least correlated tags with each emotion attribute. In this article, we used six sensory attributes and tags (marked with a dagger): energy, roughness, tempo, discontinuity, irregularity, and dynamism.

B IMPLEMENTATION OF PARAMETERS

Table 2. Influential Sensory Attributes from Section 3.3 (Left Column) and Their Implementation with Engineering Parameters (Right Column)

Sensory Attribute	Implementation
Energy & Roughness	These two sensory parameters are coupled in most vibration actuators including the C2 tactor. Since both of these sensory parameters link to *agitation*, we did not decouple them in our implementation. Past literature links a vibration's energy to its frequency and waveform [27, 35]. We increased frequency and switched to a square waveform.
Tempo	We utilized the similarities (in design parameters and hardware) reported for audio and tactile stimuli in the literature [3, 7, 11, 44]. Based on the algorithm used for increasing tempo in sound files [28], we shortened duration of pulses and silences without impacting its pitch (frequency).
Discontinuity	Due to lack of prior literature in this area, we qualitatively examined discontinuous vibrations in the *VibViz* library, then modified number and duration of silences in base vibrations, and evaluated them in pilot studies until we converged at the following definition: For discontinuous vibrations, we replaced part of each pulse with silence. For continuous vibrations, we divided the vibration to equal sections and replaced a part of each section with silence.
Irregularity	Following a process similar to *discontinuity*, we found linkages between *irregularity* and rhythm variations. Thus, we added silence with a random duration to existing silences in discontinuous vibrations or to random positions in continuous vibrations.
Dynamism	Based on *VibViz* vibrations and pilot studies, we defined this as amplitude variation and periodically decreased amplitude of pulses.

C QUALITATIVE DESCRIPTION OF EMOTION DIMENSIONS

Table 3. Participant Emotion Attribute Definitions, Aggregated for Studies 1 and 2

Emotion	Definition Pre-Interview	Definition Post-Interview
Agitating	irritating (12), nervous (10), shaking (5), angry (4), uncomfortable (4), unpleasant (3), negative (3), fast (3), random (2), strong (2), constant (2), unbalance (1), provoking (1), attention-getting (1), painful (1), moves up and down (1)	**strong** (25)†, long (6), irritating (5), **fast** (5)†, **non-rhythmic** (5)†, **irregular** (4)†, constant (3), discontinuous (3), aggressive (2), unexpected (2), urgent (2), shaking (2), unpleasant (2), alarming (2), random (2), continuous (2), high frequency (2), frequent pulses (2), different from base (1)
Lively	energetic (11), happy (10), pleasant (7), **strong** (6)†, exciting (5), holidays or party (3), full of life (3), rhythmic (3), upbeat (2), musical (2), alert (2), colorful (1), noisy (1), young (1), confident (1), tickling (1), bright (1), buzzy (1)	**strong** (14)†, **fast** (13)†, rhythmic (10), short pulses (6), discontinuous (3), regular (3), happy (2), upbeat (2), light (1), smooth (1), increase in strength over time (1)
Strange	weird (16), unfamiliar (13), unexpected (6), unpleasant (3), unnatural (3), uncomfortable (2), scary (2), inconsistent (1), disturbing (1), creepy (1), different (1), cautious (1), non-rhythmic (1), patterned vibration (1)	**off-rhythm** (14)†, different from base (8), random pattern (8), unfamiliar (7), **irregular** (6)†, unexpected (4), weird (3), unnatural (2), negative (1), extreme (1), uncomfortable (1), nonsensical (1), long (1), shorter pulses (1), fast (1)

We extracted adjectives and noun phrases and counted participant references to them or their apparent synonyms. The resulting lists are ordered by the most frequent phrases, with the total count presented in parenthesis. Frequently used phrases ($n \geq 4$) for more than one emotion attribute are in bold (and marked with a dagger).

D SPECIFICATION OF BASE VIBRATIONS AND THEIR DERIVATIVES

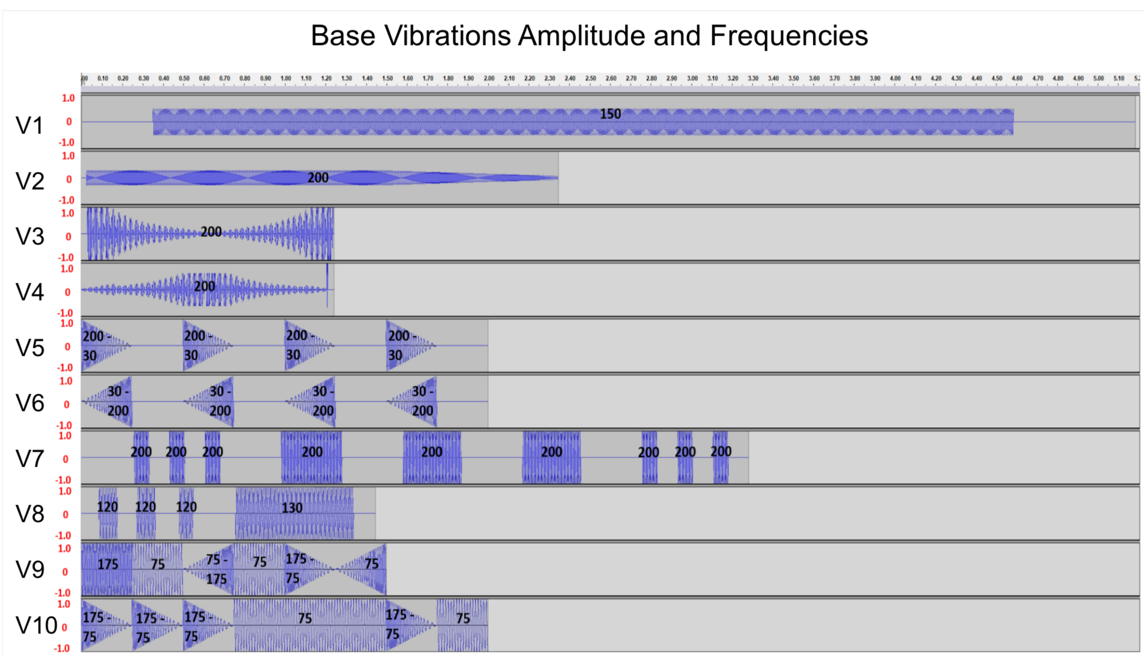


Fig. 12. Amplitude and frequency specifications for the 10 base vibrations in our studies.

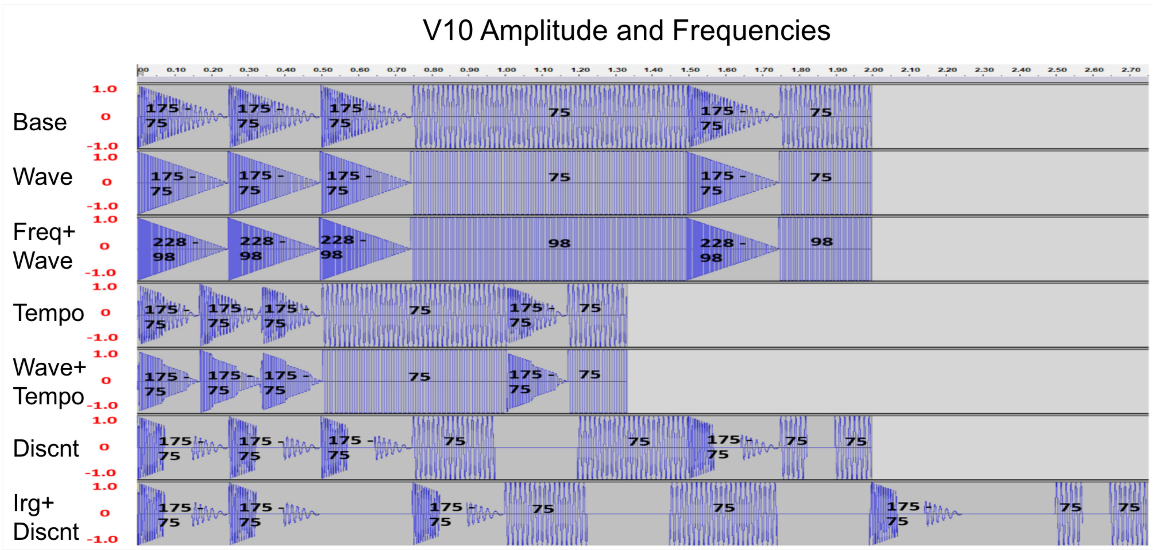


Fig. 13. Amplitude and frequency specifications for V10 and its derivatives in Study 1.

E AVERAGE VIBRATION RATINGS IN STUDIES 1 AND 2

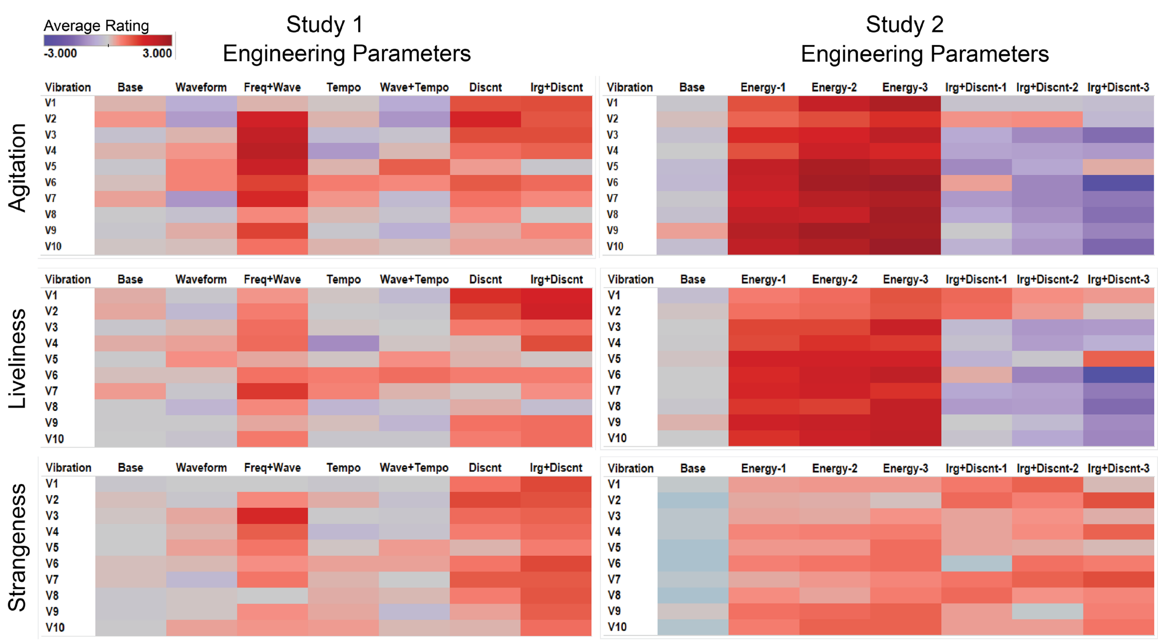


Fig. 14. Average emotion ratings across the 10 basis vibrations.

REFERENCES

[1] Audacity. 2015. Audacity software. Retrieved January 24, 2015 from http://audacity.sourceforge.net/.

[2] Jan O. Blom and Andrew F. Monk. 2003. Theory of personalization of appearance: Why users personalize their pcs and mobile phones. *J. Hum.-Comput. Interact.* 18, 3 (2003), 193–228.

[3] Lorna M. Brown, Stephen A. Brewster, and Helen C. Purchase. 2006. Tactile crescendos and sforzandos: Applying musical techniques to tactile icon design. In *CHI'06 Extended Abstracts on Human Factors in Computing Systems (CHI EA'6)*. 610–615.

[4] L. Brunet, C. Megard, S. Paneels, G. Changeon, J. Lozada, M. P. Daniel, and F. Darses. 2013. Invitation to the voyage: The design of tactile metaphors to fulfill occasional travelers' needs in transportation networks. In *Proceedings of the IEEE World Haptics Conference (WHC'13)*. 259–264. DOI: http://dx.doi.org/10.1109/WHC.2013.6548418

[5] Andrew Chan, Karon MacLean, and Joanna McGrenere. 2008. Designing haptic icons to support collaborative turn-taking. *Int. J. Hum.-Comput. Stud.* 66, 5 (2008), 333–355.

[6] W. J. Conover and Ronald L. Iman. 1981. Rank transformations as a bridge between parametric and nonparametric statistics. *Am. Stat.* 35, 3 (1981), 124–129.

[7] EAI. 2015. Engineering Acoustics, Inc. Retrieved January 24, 2015 from http://www.atactech.com/PR_tactors.html.

[8] Martin Evening. 2013. *The Adobe Photoshop Lightroom 5 Book: The Complete Guide for Photographers*. Pearson Education.

[9] Google. 2016. Google Play Music. Retrieved October 21, 2016 from play.google.com/music/listen#/now.

[10] Matthew J. Hertenstein and Sandra J. Weiss. 2011. *The Handbook of Touch: Neuroscience, Behavioral, and Health Perspectives*. Springer Publishing Company.

[11] Eve Hoggan and Stephen Brewster. 2007. Designing audio and tactile crossmodal icons for mobile devices. In *Proceedings of the 9th ACM International Conference on Multimodal Interfaces (ICMI'07)*. 162–169.

[12] Instagram. 2016. Instagram. Retrieved October 21, 2016 from https://www.instagram.com/?hl=en.

[13] Ali Israr, Siyan Zhao, Kaitlyn Schwalje, Roberta Klatzky, and Jill Lehman. 2014. Feel effects: Enriching storytelling with haptic feedback. *ACM Trans. Appl. Percept.* 11, 3 (2014), 11:1–11:17.

[14] Emilia Koskinen, Topi Kaaresoja, and Pauli Laitinen. 2008. Feel-good touch: Finding the most pleasant tactile feedback for a mobile touch screen button. In *Proceedings of the 10th International Conference on Multimodal Interfaces (ICMI'08)*. ACM, New York, NY, 297–304. DOI: http://dx.doi.org/10.1145/1452392.1452453

[15] Dae H. Kwak, Galen E. Clavio, Andrea N. Eagleman, and Ki T. Kim. 2010. Exploring the antecedents and consequences of personalizing sport video game experiences. *Sport Market. Quart.* 19, 4 (12 2010), 217–225.

[16] Jaebong Lee, J. Ryu, and S. Choi. 2009. Vibrotactile score: A score metaphor for designing vibrotactile patterns. In *Proceedings of the IEEE World Haptics Conference (WHC'09)*. 302–307. DOI: http://dx.doi.org/10.1109/WHC.2009.4810816

[17] Henry Lieberman, Fabio Paternò, Markus Klann, and Volker Wulf. 2006. End-user development: An emerging paradigm. In *End User Development*. Springer, 1–8.

[18] Wendy E. Mackay. 1991. Triggers and barriers to customizing software. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI'91)*. 153–160. http://dl.acm.org/citation.cfm?id=108867

[19] Karon E. MacLean, Oliver Schneider, and Hasti Seifi. 2017. Multisensory haptic interactions:Understanding the sense and designing for It. In *The Handbook of Multimodal-Multisensor Interfaces*. ACM Books.

[20] Sampada Marathe and S. Shyam Sundar. 2011. What drives customization?: Control or identity? In *Proceedings of ACM SIGCHI Conference on Human Factors in Computing Systems (CHI'11)*. 781–790. http://dl.acm.org/citation.cfm?id=1979056

[21] Francis McGlone, Ake B. Vallbo, Hakan Olausson, Line Loken, and Johan Wessberg. 2007. Discriminative touch and emotional touch. *Can. J. Exp. Psychol.* 61, 3 (2007), 173.

[22] Joanna McGrenere, Ronald M. Baecker, and Kellogg S. Booth. 2007. A field evaluation of an adaptable two-interface design for feature-rich software. *ACM Trans. Comput.-Hum. Interact.* 14, 1 (2007), 3.

[23] MoodFuse. 2016. MoodFuse. Retrieved October 21, 2016 from moodfuse.com.

[24] Musicovery. 2016. Musicovery. Retrieved October 21, 2016 from http://musicovery.com/.

[25] Piia Nurkka. 2013. "Nobody other than me knows what i want": Customizing a sports watch. In *Proceedings of the Conference on Human-Computer Interaction (INTERACT'13)*. Lecture Notes in Computer Science, vol. 8120. Springer, Berlin, 384–402.

[26] Uran Oh and Leah Findlater. 2013. The challenges and potential of end-user gesture customization. In *Proceedings of Athe CM SIGCHI Conference on Human Factors in Computing Systems (CHI'13)*. 1129–1138. http://dl.acm.org/citation.cfm?id=2466145

[27] Conor O'Sullivan and Angela Chang. 2006. *An Activity Classification for Vibrotactile Phenomena*. Springer, Berlin, 145–156. DOI: http://dx.doi.org/10.1007/11821731_14

[28] Olli Parviainen. 2016. SoundTouch Algorithm. Retrieved September 24, 2016 from http://www.surina.net/soundtouch/.

[29] Mark Paterson. 2007. *The Senses of Touch: Haptics, Affects and Technologies*. Berg.

[30] Photoshop. 2016. Adobe Photoshop. Retrieved October 23, 2016 from https://www.adobe.com/ca/products/photoshop.html.

[31] Propellerhead. 2016. Figure, on Google Play Store. Retrieved October 21, 2016 from https://www.propellerheads.se/products/figure/manual/introduction/.

[32] Jonghyun Ryu, Jaemin Chun, Gunhyuk Park, Seungmoon Choi, and Sung H. Han. 2010. Vibrotactile feedback for information delivery in the vehicle. *IEEE Trans. Haptics* 3, 2 (Apr. 2010), 138–149. DOI: http://dx.doi.org/10.1109/TOH.2010.1

[33] Greg Saul, Manfred Lau, Jun Mitani, and Takeo Igarashi. 2011. SketchChair: An all-in-one chair design system for end users. In *Proceedings of the 5th ACM International Conference on Tangible, Embedded, and Embodied Interaction (TEI'11)*. 73–80.

[34] Oliver S. Schneider, Ali Israr, and Karon E. MacLean. 2015. Tactile animation by direct manipulation of grid displays. In *Proceedings of the ACM Symposium on User Interface Software and Technology (UIST'15)*. 21–30.

[35] Oliver S. Schneider and Karon E. MacLean. 2014. Improvising design with a haptic instrument. In *Proceedings of the IEEE Haptics Symposium (HAPTICS'14)*. 327–332.

[36] Oliver S. Schneider and Karon E. MacLean. 2016. Studying design process and example use with macaron, a web-based vibrotactile effect editor. In *Proceedings of the IEEE Haptics Symposium (HAPTICS'16)*. 52–58.

[37] Oliver S. Schneider, Hasti Seifi, Salma Kashani, Matthew Chun, and Karon E. MacLean. 2016. HapTurk: Crowdsourcing affective ratings of vibrotactile icons. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI'16)*. 3248–3260.

[38] Hasti Seifi, Chamila Anthonypillai, and Karon E. MacLean. 2014. End-user customization of affective tactile messages: A qualitative examination of tool parameters. In *Proceedings of IEEE Haptics Symposium (HAPTICS'14)*. 251–256.

[39] Hasti Seifi and Karon E. MacLean. 2017. Exploiting haptic facets: Users' sensemaking schemas as a path to design and personalization of experience (unpublished).

[40] Hasti Seifi, Kailun Zhang, and Karon E. MacLean. 2015. VibViz: Organizing, visualizing and navigating vibration libraries. In *Proceedings of the IEEE World Haptics Conference (WHC'15)*. 254–259.

[41] Snapseed. 2016. Snapseed, on Google Play Store. Retrieved October 21, 2016 from https://itunes.apple.com/ca/app/snapseed/id439438619?mt=8.

[42] Diane Tam, Karon E. MacLean, Joanna McGrenere, and Katherine J. Kuchenbecker. 2013. The design and field observation of a haptic notification system for timing awareness during oral presentations. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI'13)*. ACM, New York, NY, 1689–1698. DOI: http://dx.doi.org/10.1145/2470654.2466223

[43] David Ternes and Karon E. Maclean. 2008. Designing large sets of haptic icons with rhythm. In *Haptics: Perception, Devices and Scenarios*. Springer, 199–208.

[44] Jan B. F. van Erp and Michiel M. A. Spapé. 2003. Distilling the underlying dimensions of tactile melodies. In *Proceedings of Eurohaptics*, Vol. 2003. 111–120.

[45] Jacob O. Wobbrock, Leah Findlater, Darren Gergle, and James J. Higgins. 2011. The aligned rank transform for nonparametric factorial analyses using only anova procedures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'11)*. ACM, 143–146.

[46] Yongjae Yoo, Taekbeom Yoo, Jihyun Kong, and Seungmoon Choi. 2015. Emotional responses of tactile icons: Effects of amplitude, frequency, duration, and envelope. In *Proceedings of the IEEE World Haptics Conference (WHC'15)*. 235–240.

[47] Siyan Zhao, Oliver Schneider, Roberta Klatzky, Jill Lehman, and Ali Israr. 2014. FeelCraft: Crafting tactile experiences for media using a feel effect library. In *Proceedings of the Adjunct Publication of the 27th Annual ACM Symposium on User Interface Software and Technology (UIST'14)*. ACM, New York, NY, 51–52. DOI: http://dx.doi.org/10.1145/2658779.2659109

[48] Ying Zheng and John B. Morrell. 2012. Haptic actuator design parameters that influence affect and attention. In *Proceedings of the IEEE Haptics Symposium (HAPTICS'12)*. IEEE, 463–470.

Received February 2017; revised January 2018; accepted April 2018