palmScape: Calm and Pleasant Vibrotactile Signals

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Abstract. The goal of the present study was to design vibrotactile signals that support a more engaging and delightful user experience. Using a four-tactor display called *palmScape*, custom-designed signals were created to capture the essence of natural phenomena such as *breathing*, *heartbeat*, and *earthquake*. A key insight was the use of slow motions to convey aliveness in a calm manner. Fourteen participants evaluated twenty vibrotactile signals by providing valence and arousal ratings. Our custom-designed patterns were consistently rated at higher valence levels than reference signals from the literature at similar arousal levels. Eight of the sixteen custom signals occupied the fourth quadrant of the valence-arousal space that corresponds to *calm* and *pleasant* ratings, a space that is rarely occupied by other studies of vibrotactile signals. In this article, we share our design approach, signal parameters, and affective rating results. Our work will hopefully encourage more research on affective haptics.

Keywords: Design · Vibrotactile signals · Tactor array display · Affective rating · Calm · Pleasant · palmScape

1 Introduction

As vibrotactile alert signals become ubiquitous on mobile devices, the question arises as to how to devise alert signals that are rich in meaning, carry natural or intuitive messages and are generally more pleasant than a mere "buzz." In the cases of smart-watches and phones that are mostly worn on the wrist or held in the hand, the device is in frequent if not constant contact with the skin. While a somewhat annoying "buzzing" alert may be effective at getting the user's attention, it is also desirable to provide other options that engage the user in a gentler and richer manner by, for example, using broadband tactors (tactile stimulators) to optimize the sensations for each usage and context.

Studies on vibrotactile alerts tend to focus on its functional benefits (e.g., Fukumoto & Sugimura [1], Gordon and Zhai [2]) or its information contents (e.g., Brown et al. [3], Tan et al. [4]). More recently, many researchers have studied emotional responses to vibrotactile stimulation that imitate human touch. Rantala et al. [5] showed that squeeze-like signals were judged to be unpleasant and high in arousal, and signals that felt like finger touch were found to be pleasant and relaxing. Pradana et al. [6] demonstrated that vibrotactile signals can prime the valence of text messages received

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on a mobile device. In general, signals at low intensities tend to lead to neutral valence and most signals at high intensities feel annoying (low valence). It thus appears difficult to design vibrotactile signals that can lead to high valence ratings, especially at low arousal levels, by varying signal amplitude, frequency, duration, rhythm, envelope, etc. (e.g., Seifi and MacLean [7], Yoo et al. [8]). Recently, Culbertson et al. [9] and Huisman et al. [10] have investigated stroking-like signals in an attempt to stimulate the C-fibers to evoke pleasant sensations (see [11]), and Korres et al. [12] created an alarm system for pleasant awakening.

A common characteristic of tactile alert signals is that they feel "buzzy" (although Google has made it a priority to remove buzzing from its Pixel 2 and Pixel 3 phones). A major strategy in creating natural and pleasant tactile sensations is to move away from the typical high-frequency "buzzing" signals and instead use lower frequencies for slow motions, gentle roughness, and flutter sensations. The need for richer haptic displays was well recognized by researchers developing haptic devices for sensory substitution. For example, Leotta et al. [13], Rabinowitz et al. [14] and Reed et al. [15] built an artificial mechanical-face around a plastic skull, Eberhardt et al. [16] built the OMAR system for the hand, and Tan and Rabinowitz [17] and Tan et al. [4] built and tested a multi-finger tactual display. These devices were designed to deliver kinesthetic (large-amplitude, low-frequency) motions, tactile (small-amplitude, high-frequency) vibrations, and the sensations associated with the intermediate frequencies and amplitudes, to one or more digits. Bolanowski et al. [18], Mountcastle et al. [19, 20] and Tan [21] have shown that along the frequency continuum, signals on the order of a few Hertz are perceived as slow motions, those within 10–70 Hz feel fluttery (at small amplitude) or rough (at large amplitude), and those above 150 Hz are perceived as smooth vibrations. The dominant frequency of many natural phenomena, such as breathing (12–20 breaths per minute) and heartbeat (60–100 beats per minute), fall into the low-frequency, slow-motion range of 1.67 Hz or slower. Incorporating signals at very low frequencies into our vibrotactile design is an important strategy of the present work.

Russell [22] proposed the circumplex model for subjective affective ratings which is used by most studies on affective haptics. The higher (or lower) the valence, the more pleasant (or unpleasant) the emotion is. The higher (or lower) the arousal, the more exciting (or calm/relaxing) the signal is perceived to be. While some studies use only positive integers for valence and arousal ratings (e.g., Bradley and Lang [23] and Lang et al. [24] used 1 to 9), others use a symmetric positive/negative scale (e.g., Yoo et al. [8] and Bradley and Lang [25] used −4 to 4). Since affective ratings are relative in nature, ratings along a [1, 9] scale can be converted to a [−4, 4] scale and vice versa. The present study uses the circumplex model for validation of the vibrotactile signals we have designed, and compare our results to the findings from published studies.

The present research asks the question of how to delight a user with calm and pleasant vibrotactile alerts. Our work focuses on vibrotactile stimulation, the most common form of haptic alerts. We use multiple tactors in order to expand the spatial contents of the tactile experience. We choose the palm to be the stimulation site due to the relatively large size of the broadband tactors used in our research and the ease with which one can simply place the palm on the tactor array (Fig. 1). Our goal is to explore the possibility of designing vibrotactile signals that are judged to be in the fourth quadrant of the valence-arousal space – *calm* and *pleasant*.

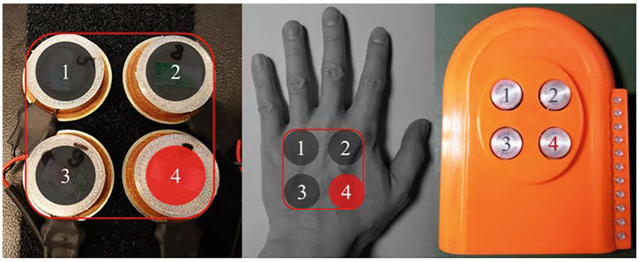

Fig. 1. *palmScape*: (left) the experimental apparatus, (middle) tactor locations under the left palm, and (right) a wireless prototype for demonstration

2 Design Approach

This section outlines the design principles and guidelines that we have followed during the present research. Our work draws inspiration from Cohen et al. [26], Israr et al. [27] and MacLean [28] that outline strategies for designing signals that are explicitly paired with linguistic phrases, and/or associated with natural events, in addition to heuristics. Our signal design follows three design principles and five guidelines, as outlined below.

2.1 Design Principles

I. *Beyond Simple Vibration*
As discussed above, a key strategy of the present research is to introduce low-frequency components into the design of vibrotactile signals to enrich their *expressiveness*. Purely vibrational signals are homogeneous, monotonic, narrow in its expressiveness, and neutral in emotional content. They correspond to a narrow range of sensations we experience in our everyday lives. To overcome the limitations, tactors that move at very low frequencies with sufficient torque are needed to render soft and gentle motions in the z-direction (i.e., perpendicular to the skin) to express deformations and movements such as breathing and heartbeat.

II. *Natural and Delightful*
We are exposed to frequent vibrotactile feedback from smartphones and wearable devices in our daily lives. It is imperative that the vibrotactile feedback on our skin be comfortable, informative and pleasant. To achieve this goal, we take a design approach that is based on natural metaphors to maximize the natural expressiveness of our haptic signals and invite empathy from the users, bringing pleasure and delight to people.

III. *Simple and Distinctive*
We want to achieve simple and distinctive signal patterns that are unique, recognizable and easily learned. By distilling the essence of natural phenomena and simplifying our signals to carry the minimum information required for expressing the physical characteristics of natural events, we can maximize the consensus of users' interpretations of our custom-designed vibrotactile icons. The result is a collection of vibrotactile signals that are easily distinguishable, quickly learned and highly recognizable.

2.2 Design Guidelines

i. *Natural Metaphors*
We sought to understand the physical characteristics of natural phenomena, and designed haptic signals that matched their features. For example, we focused on the *aliveness* of heartbeat, breathing, and pulsation. We applied *randomness* in creating twinkles, bubbles, and raindrops. We incorporated *repeatability* in ripples, cicadas, (horse) galloping, and frog (croaking). For earthquake and thunder, we used *gradualness* to build up or dissipate energy.

ii. *Richness Through Dimensions*
Findings from research on tactile icons (see Azadi and Jones [29], Barralon et al. [30], Brown et al. [31] and MacLean and Enriquez [32]) and tactile speech communication (see Rabinowitz et al. [33] and Tan et al. [4]) have clearly established the use of multiple signal dimensions to enrich the tactile experience. Figure 2 illustrates the progression from a single-point display to a 2-tactor linear display, to a 2-by-2 planar display, and then to our palmScape display that incorporates slow motions along the z-axis.

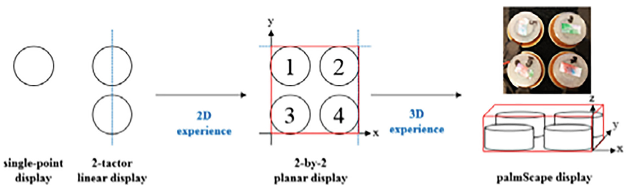

Fig. 2. Expanding the spatial richness of a tactile display from a single-point vibration to a truly 3D experience

In addition to expanding the spatial dimension of a display, we also broadened the use of frequency by (1) lowering the *carrier frequency* (to ≤ 3 Hz) to create slow motions along the z-axis (e.g., breathing), and (2) lowering the *amplitude-modulation frequency* (to ≤ 1 Hz) to express a gradual change of intensity (e.g., earthquake). Figure 3 provides a few examples.

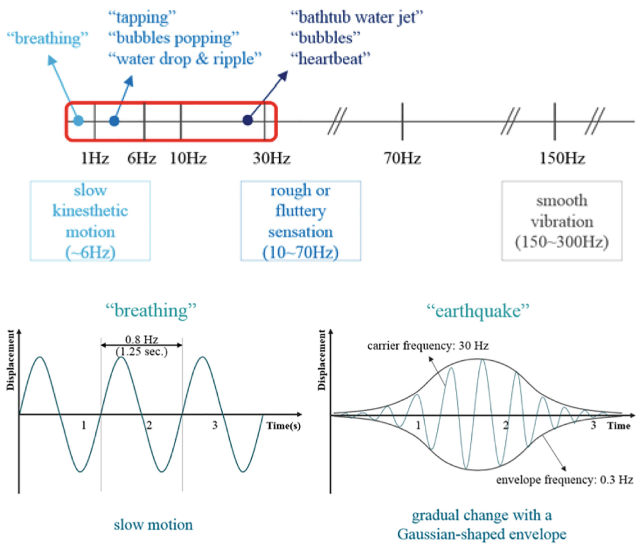

Fig. 3. Top: Illustration of the use of lower frequencies for designing vibrotactile icons. Bottom: Waveforms for "breathing" that evokes the sensation of holding a small puppy in the palm (bottom-left panel), and "earthquake" that conveys a gradual built-up and dissipation of rough, rumbling sensations on the skin (bottom-right panel).

iii. *Parts and Whole*

When dealing with a complex physical phenomenon, we approached the design of vibrotactile icons by dividing one phenomenon into multiple events. The heartbeat signal was created by first identifying the four main events (e.g., expansion of the left atrium) during one cycle of a heartbeat. Then, we found a good representation of each event, and combined them into one composite vibrotactile icon with proper temporal offsets of the four events (Fig. 4).

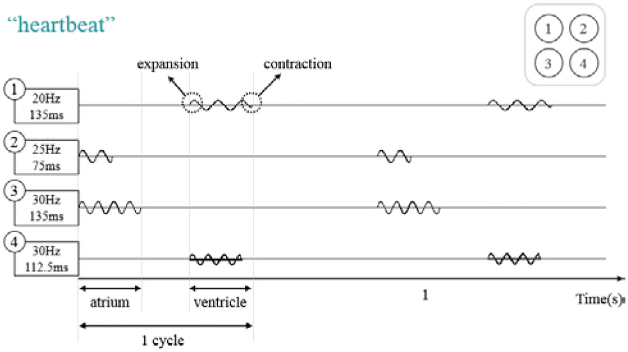

Fig. 4. Illustration of "heartbeat." Shown are the four main events making up a heartbeat and the tactors used to represent each event. The upper-right corner shows tactor numbering.

iv. *Simplicity*

When it comes to designing distinctive and memorable vibrotactile icons, less is more. This is because of factors such as temporal and intensive masking, limited spatial attention span, poor haptic numerosity judgment, and finite temporal-order judgment capability (see Verrillo and Gescheider [34]). Therefore, care should be taken to remove signal components that are redundant, can potentially mask other components, or otherwise do not contribute much to the overall perception. Parameters should be judiciously chosen and used sparingly. For example, the "cicadas" signal consists of a high-pitched 120-Hz background noise with a 32-Hz amplitude modulation for added roughness, and a few bursts of a 60-Hz signal modulated at 2 Hz (Fig. 5). The latter cuts in four times and then fades out.

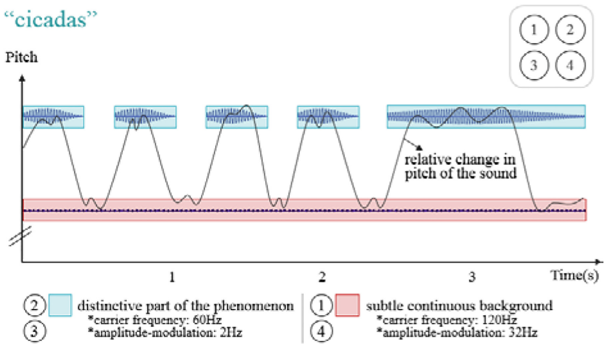

Fig. 5. Illustration of "cicadas"

v. *Randomness*

While some natural phenomena such as heartbeat and breathing carry a regular rhythm, others exhibit a less predictable pattern. When designing the vibrotactile icons for the latter, the multiple parameters making up the haptic signal were varied to represent the randomness of the phenomenon. In the case of a “raindrop” (Fig. 6), for example, the inter-stimulus interval between two adjacent “drops” varied from 70.4 to 316.8 ms, the frequency varied randomly within 80 to 120 Hz, and the stimulation location was randomized among the four tactors (see also Israr et al. [27]). Although we kept the signal amplitude constant, the perceived intensity varied due to frequency variations. We found it important to limit the range of frequency variations in order to create a subtle and natural fluctuation in perceived vibrotactile intensity and pitch.

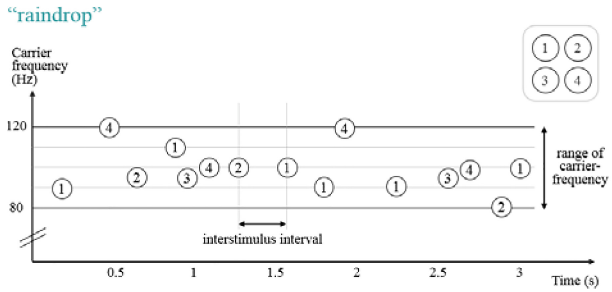

Fig. 6. Illustration of “raindrop”

In addition to the aforementioned design guidelines, we also employed other design considerations. For example, the musical elements of rhythm were used to promote a sense of familiarity with the user. Starting the design process with a sound analysis was found to be conducive to accessing the expression of the vibrotactile phenomenon in a more straightforward manner. We also focused on barely detectable or low-intensity signals to create subtle sensations (e.g., “twinkle”). For “thunder,” an intense and short beginning ($\sim$10 ms) led to the feeling of a strong impact. And a satisfying “knock” was achieved with a fast drop ($\sim$5 ms) from its peak amplitude.

3 Custom-Designed Vibrotactile Signals

A total of 16 custom-designed vibrotactile signals were created using the design approach described so far. They were inspired by a wide range of natural phenomena. The parameters for the 16 signals vary along many dimensions in ways that depend on the characteristics of the corresponding natural phenomenon. Table 1 shows the key parameters of the 16 signals (#1–16) and 4 other signals (#17–20, explained in Sect. 4.1, Stimuli, on p.10).

Table 1. The 20 Stimuli used in the present study

No.	Stimulus name	Carrier [Envelope] frequency (Hz)	Expression [applied design guidelines]
1	Breathing	0.8	Extremely slow motion [i, ii]
2	Earthquake	30 [0.3]	Gradualness [i, ii]
3	Heartbeat	20–30	Smooth beating [i, ii, iii]
4	Raindrop	80–120	Subtle pulse [i, v]
5	Elephant trod	20	Deep pounding sensation [i, ii]
6	Tapping	2	Tapping sensation [i, ii]
7	Thunder	30, 135, 150 [0.3]	Strong spatial impact [i, ii, iii]
8	Twinkle	300	Tickling sensation [i, iv, v]
9	Bubbles	20	Soft pushing [i, ii]
10	Water drop & ripple	5–10, 180, 300 [10]	Wavy sensation [i, ii, iii, v]
11	cicadas	60, 120 [0.5, 2, 32]	Roughness [i, ii, iii, iv]
12	Bathtub water jet	10 [0.3]	Medium-soft pushing [i, ii, iv]
13	Frog	50, 120 [1.7, 16]	Roughness [i, ii, iii, iv]
14	(horse) Galloping	3–7, 180, 300	Rhythm/hard tapping [i, ii, iii]
15	Knock	30, 300	Knocking sensation [i, ii]
16	Bubbles popping	2	Slow push/subtle popping [i, ii, iii]
17	*Alarm [12]*	60–200	Co-varying frequency and location
18	*Notification 1 [8]*	300	Strong vibration (1 s, 1.4 g)
19	*Notification 2 [8]*	60	Soft vibration (1 s, 0.12 g)
20	*Notification 2 [8]*	150	Medium vibration (1 s, 0.39 g)

Breathing (#1) is a slow motion in the z-direction with a 2-mm displacement at 0.8 Hz to express the aliveness of a small creature (see Fig. 3). ***Earthquake*** (#2) is a 30-Hz vibration modulated with a 3.3-s Gaussian-shaped envelope to convey a gradual build-up and dissipation of energy (see Fig. 3). ***Heartbeat*** (#3) consists of pumping-like 20-30 Hz vibrotactile pulses corresponding to the contractions of the four chambers of the human heart (Fig. 4). ***Raindrop*** (#4) expresses the feeling of a sprinkle of rain with infrequent and sporadic gentle pulses (Fig. 6). ***Elephant trod*** (#5) is a 20-Hz vibration delivered to all 4 tactors simultaneously to express a deep pounding effect. ***Tapping*** (#6) consists of a carrier frequency of 2 Hz with a rapidly-falling envelope from its peak amplitude for the tapping sensation. ***Thunder*** (#7) stresses the initial impact from rumbling and lightning using 135-Hz and 150-Hz vibrations at high amplitudes, then attenuates the signal amplitude gradually following a 3.3-s Gaussian-shaped envelope. ***Twinkle*** (#8) expresses the feeling of small particles spreading in space with 300-Hz vibrotactile pulses at low intensities at random tactor locations. ***Bubbles*** (#9) delivers the sensation of bubbles rising from a water surface with soft 20-Hz vibrations at varying tactor locations. ***Water drop & ripple*** (#10) mimics a water droplet hitting a water surface, resulting in waves that expand spatially. It starts with a gentle 180-Hz pulse on tactors #1 and #4 for "water drop," followed by 5-Hz or 10-Hz "ripples" delivered to all four tactors. ***Cicadas*** (#11) expresses the roughness of crying cicadas, as illustrated in Fig. 5. ***Bathtub water jet*** (#12) is a 10-Hz vibration with a 0.3-Hz amplitude modulation delivered randomly to one of the tactors. It simulates a continuous water flow with soft and variable pressure on the palm. ***Frog*** (#13) uses two superimposed frequencies of 50 and 120 Hz with amplitude modulations at 1.7 Hz and 16 Hz to characterize the croaking sound and the movement of the frog's vocal sac. ***Galloping*** (#14) consists of multiple carrier frequencies at 3, 5, 7, 180, and 300 Hz to express rhythmic, rigid tapping on the ground. ***Knock*** (#15) contains short vibrotactile pulses with superimposed components at 30 Hz and 300 Hz to realize the feel of knocking by knuckles. ***Bubbles popping*** (#16) uses a 2-Hz vibration with a fast-decaying amplitude to represent slow pushing and popping.

4 Affective Rating Experiment

To assess the emotional response to our custom-designed vibrotactile signals, an affective rating experiment was conducted based on Russell's circumplex model of affect [22].

4.1 Methods

Participants. Fourteen participants (P01–P14; 7 males and 7 females; age range 19–38 years old, average age 24.4 ± 4.4 years old) took part in the affective rating experiment. All but one (P12) are right handed. None had known sensory or motor impairments with their hands. Three of the participants are native English speakers and the others speak English fluently as a second language. All reported prior haptic experience with smart phones, game consoles and controllers, smart watches, electric toothbrushes, or massage devices. Each participant signed an IRB-approved informed consent form, and received 15 USD in compensation of their time.

Apparatus. The *palmScape* device consists of a 2-by-2 tactor array placed on a round plate filled with silicone rubber (see left panel of Fig. 1). The tactors (Tectonic Elements, Model TEAX13C02-8/RH) are wide-bandwidth speakers with a constant impedance of 8 Ω in the frequency range of 50 to 2,000 Hz, except for a peak near 600 Hz. Each tactor measures about 30 mm in diameter and 9 mm in thickness. A MATLAB program generated four independent waveforms that were synchronously converted to four analog audio signals by a MOTU 24Ao device. The signals were then amplified to drive the four tactors, respectively. We verified with an accelerometer (Kistler 8794A500) that the tactor responses followed the signal waveforms from about 300 Hz down to <1 Hz.

Calibration and Equalization of Intensity. Prior to the main experiment, the detection threshold for each participant was estimated and the perceived intensities of the four tactors were equalized. Individual detection thresholds were measured at 150 Hz for tactor #4 under the left thenar eminence (Fig. 1, middle panel). The detection thresholds were measured using a three-interval, two-alternative, one-up two-down adaptive forced-choice procedure with trial-by-trial correct-answer feedback (see Jones and Tan [35]). The vibration was presented with equal *a priori* probability in one of three temporal intervals, and no signal was presented during the remaining two intervals. Each interval was cued visually on a computer monitor. The participant's task was to identify the interval containing the vibration. The level of the vibration was adjusted adaptively using the one-up, two-down rule to estimate the stimulus level required for 70.7% correct detection. Each time the participant made a mistake with the response, the vibration level was increased (i.e., one-up). After two consecutive correct responses from the participant, the vibration level was decreased (i.e., two-down). The adaptive procedure is an efficient way to place vibration levels near detection thresholds on most of the trials.

The perceived intensity of the four tactors was equalized using a method of adjustment (see Jones and Tan [35]). The reference vibration was played on tactor #4. The level of each of the three remaining tactors was then adjusted by the participant so that its strength matched that of the reference tactor. This continued until the participant was satisfied that the reference and test signals were at equal perceived intensity. The results were saved in a level-adjustment table for each participant.

The results from the two steps were used to ensure that the perceived signal intensities, defined in dB above individual detection thresholds, were similar for each participant.

Stimuli. The stimuli included the 16 custom-designed vibrotactile signals (#1–16) and 4 reference signals (#17–20), for a total of 20 stimuli (see listing in Table 1). The reference signals were selected from two earlier studies by Korres et al. [12] and Yoo et al. [8]. Signal #17 was modified from a vibrotactile alarm signal that was rated as the most pleasant (highest valence) in Korres et al.'s study [12]. It consisted of six 300-ms long pulses with a 120-ms overlap that moved over the tactors while the magnitude increased from 0.25 to 1.25 g and the frequency co-varied from 60 to 200 Hz. Signals #18 to #20 were the same as the three signals in Yoo et al.'s study [8] associated with the highest valence ratings at the highest intensity (300-Hz, 1000-ms at 1.4 g), the lowest intensity (60-Hz, 1000-ms at 0.12 g) and an intermediate intensity (150-Hz, 1000-ms at 0.39 g), respectively. The valence and arousal ratings for signal #20 were located in a neutral region near the origin of the valence-arousal space as reported by Yoo et al. [8].

4.2 Procedures

The participants were asked to place their left palm gently on *palmScape* with tactor #4 right under the thenar eminence and the other three tactors covered by the palm (Fig. 7). The participants were asked to maintain a light contact and avoid pressing down too hard on the tactors. They were introduced to the graphic icons adopted from Bradley and Lang [25] and the 9-point integer scale marked under the icons (see Fig. 8). The experimenter then explained the circumplex model, and asked the participants to familiarize themselves with two example stimuli: one at a high intensity and roughness (250-Hz carrier, 32-Hz

Fig. 7. Experimental setup: (left) noise-reduction headset, the *palmScape* display, elbow support, computer monitor, and mouse; (right) a participant in the middle of the affective rating experiment.

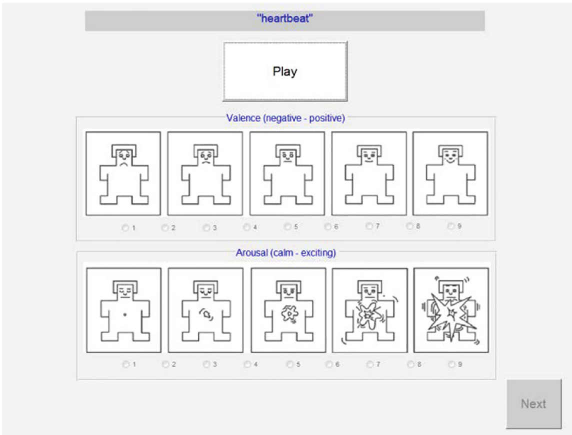

Fig. 8. Computer screen as seen by the participants

amplitude modulation envelope, 1000-ms duration, peak at 4.19 g) and the other at a lower intensity (25-Hz carrier, no modulation, 25-ms duration, peak at 1.17 g).

The main task required the participants to rate the valence and arousal of the 20 vibrotactile signals using integers between 1 and 9. Each signal was presented 5 times, and the signal sequence was randomized for each participant. On each trial, the participant saw the text label for the vibrotactile signal presented, felt the signal, and entered the two integers corresponding to the perceived valence and arousal of the signal (Fig. 8). The participant completed 4 blocks of 25 trials, with a 3-min mandatory break between the blocks to prevent fatigue. The affective rating experiment lasted between 19 min to 55 min per participant.

5 Results and Discussion

The affective ratings for all stimuli are shown in Fig. 9 as filled dots for the custom-designed signals #1–16 and filled squares for the reference signals #17–20. The position of each filled dot or square corresponds to the (valence, arousal) coordinates averaged over all 70 pairs of ratings (14 participants × 5 rating pairs per stimulus). The boxed number next to each filled symbol corresponds to the stimulus number as listed in Table 1. The two blue lines connect the 4 reference signals #17–20. Across the 14 participants, the standard deviations of valence ratings for the 20 stimuli (not shown) ranged from 1.1 to 2.3 with a mean of 1.7. The standard deviations of arousal ratings (not shown) ranged from 1.1 to 1.8 with a mean of 1.4.

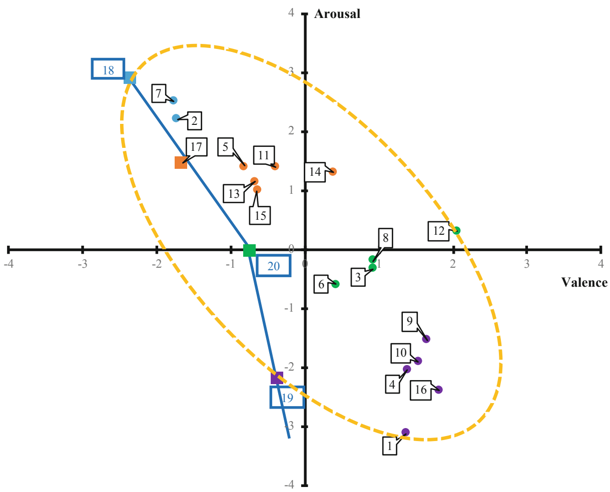

Fig. 9. Experimental results from the present study. The yellow ellipse encloses all data points. (Color figure online)

Three observations can be made from Fig. 9. When appropriate, we compare our results to the studies by Wilson and Brewster [36] and Yoo et al. [8] that used sinusoidal vibrations that varied in amplitude, frequency, duration and modulation envelope (only Yoo et al. used modulation [8]). In contrast, the present study employed complex and custom-designed waveforms. Firstly, 8 out of the 16 signals in the present study successfully landed in the fourth quadrant that corresponds to signals that are *calm* and *pleasant*. In comparison, 4 to 6 signals out of 18 from Wilson and Brewster [36] had affective ratings in the fourth quadrant (2 of the signals were near the origin of the valence-arousal space). Seven (7) out of 85 signals in Yoo et al. [8] were in the fourth quadrant.

Secondly, the 20 filled symbols cluster around a line with a slope of –1, indicating a negative correlation of valence and arousal ratings from the present study. The signals with higher arousal levels tend to be perceived as less pleasant, and those with lower arousal levels more pleasant. The affective ratings from Wilson and Brewster [36] show a similar trend of clustering around a line of negative slope. However, the data from Yoo et al. [8], reproduced in Fig. 10 below, show a very different pattern. The three red circles show the valence-arousal coordinates of signals #18–20 obtained in Yoo et al. [8]. At low arousal levels, the range of valence is quite small. At high arousal levels, valence ratings skew slightly towards the negative values.

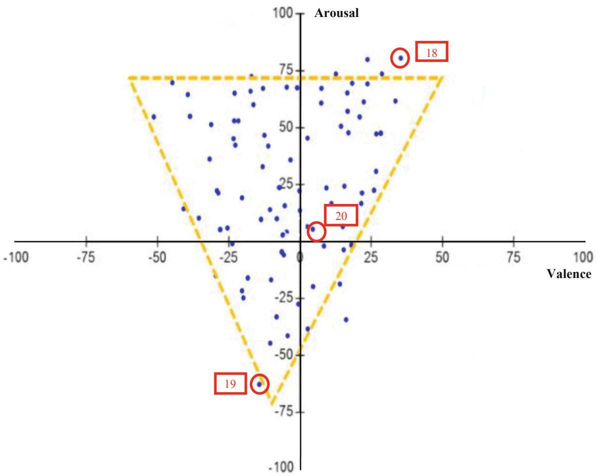

Fig. 10. Results from Yoo et al. [8], redrawn to show all the affective ratings and the (yellow) triangle enclosing most of the data points. (Color figure online)

Thirdly, it can be seen in Fig. 9 that given similar arousal ratings, the four reference signals received the lowest valence ratings. The four colors of the filled symbols encode the four stimulus groups according to the arousal ratings of the four reference signals: purple = low arousal (#19); green = medium arousal (#20); orange = medium-high arousal (#17); and blue = high arousal (#18). The 16 stimuli designed in the present study all felt more pleasant than the reference signals. The differences in valence ratings between the filled dots and the filled square in each color group are shown in Fig. 11 below. Our custom-designed signals were rated more positively along the valence axis by an overall average of 1.41 when compared to the data from Korres et al. [12] and Yoo et al. [8]. The averages according to color groups were, in descending orders, 1.91 (purple), 1.82 (green), 1.01 (orange), and 0.31(blue).

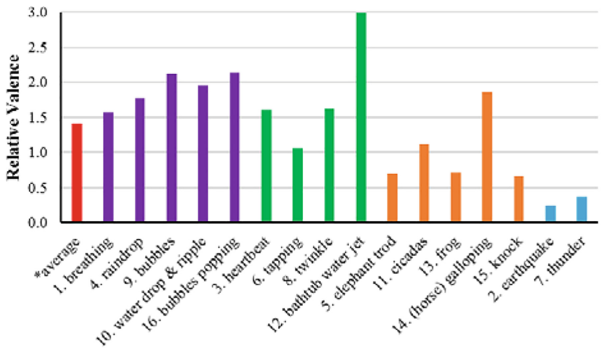

Fig. 11. Increase in valence ratings for stimuli #1–16 as compared to the reference stimuli #17–20 at similar arousal ratings, calculated from the blue lines in Fig. 9. (Color figure online)

The signals that are most calm (low arousal) and pleasant (high valence) are the purple filled dots. They consist of signal #1 (breathing), #4 (raindrops), #9 (bubbles), #10 (water drop & ripple) and #16 (bubbles popping). These signals all contain some form of slow motions except for #4, confirming our design approach of using slow motions to achieve calm and pleasant vibrotactile icons. Among the green-filled dots, #12 (bathtub water jet) has the highest valence rating, followed by #3 (heartbeat) and #8 (twinkle). Again, #3 and #12 contain low-frequency movements. Stimuli #4 (raindrops) and #8 (twinkle) are both light and slightly irregular, another winning combination for a delightful vibrotactile experience.

Note that we used text labels for the natural phenomena corresponding to our custom-designed vibrotactile icons during the experiment. Unlike the study by Yoo et al. [8] where signal parameters for vibrotactile stimuli were systematically varied and the resultant signals were rated by the participants without additional cues, the vibrotactile signals in the present study were inspired by the natural phenomena that they represent. Therefore, we provided our participants with text labels to set the proper context for the interpretation of the vibrotactile signals. This approach allowed us to explore a broader range of emotions through custom-designed vibrotactile feedback with spatial representation to engage users in an authentic and natural experience. Our daily experience is always multisensory and multimodal, and sensory signals presented in isolation can be difficult to interpret without a context. Our approach is similar to the selection of auditory ring tones on mobile and handheld devices. We first select a word or phrase from a list, listen to the auditory alert associated with it, and then select the best ring tone. The word or phrase serve to set the context for the ring tones so they can be remembered and recognized later. We envision the vibrotactile icons developed in the present study to be used in a similar manner in the future.

Anecdotal comments collected after the experiment through a debriefing questionnaire indicated that most participants found the text labels and the respective vibrotactile signals to match well except for two cases. Two participants found a weak connection between "frog" and the signal it represents, and another two participants preferred the "earthquake" signal to be stronger.

6 Concluding Remarks

The present research set out to broaden the expressive range of vibrotactile icons by creating a more realistic and natural vibrotactile experience. We believe that users of mobile devices will be more receptive to calm and pleasant alerts that engage the user in a gentler manner. This will help reduce "buzzing" and the stress associated with the constant reminder and alerts from our daily living. As smaller actuators with wide bandwidth become available, multiple tactors can be installed in game controllers, computer mice, mobile phones, tablets, arm bands, wrist bands, and even smart watches. Users of the devices will be able to select a tacton (tactile icon) from a list, just like we are able to choose a ring tone from a pull-down menu. We envision a day when people shop for handheld and mobile devices for their delightful haptic effects, and calm and pleasant haptic alerts become an integral part of our digital life.

The most significant finding of the present study is that we succeeded in creating eight vibrotactile stimuli that reside in the fourth quadrant of the valence-arousal space, a region that has rarely been occupied by similar attempts before (although see Wilson and Brewster [36] and Yoo et al. [8]). These signals often brought a smile to the person experiencing it for the first time. Some signals such as #12 (bathtub water jet) helped people relax. Others, for example, #1 (breathing), were "controversial." Some people loved the signal because it made them think of their favorite pets, and others found it "creepy" because it felt eerily alive even though it was relatively low in arousal ratings. The anecdotal notes are good indications that the emotional responses to some of our signals are visceral, and not based merely on the text labels or arbitrary and abstract mapping of signals and their meanings.

Our experimental results validated our design approach based on natural and familiar physical phenomena. It appears that systematically varying the parameters that make up a sinusoidal waveform may not be sufficient for creating pleasant-feeling signals (although it is difficult to directly compare the affective ratings from different experiments due to the relative nature of the ratings). In the future, we will compare the affective ratings of the same twenty custom-designed vibrotactile signals with or without text labels to investigate the effect of text labels on our vibrotactile stimulus set. Then, we will expand the range of affect that can be expressed with vibrotactile signals through further design exercises. We will also explore the affective ratings of vibrotactile patterns designed with one or two tactors to be more compatible with the requirements of mobile and handheld devices.

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