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Psychophysical Validation of Interleaving Narrowband Tactile Stimuli to Achieve Broadband Effects

Juan S. Martinez[1], *Member, IEEE,* Hong Z. Tan[1], *Fellow, IEEE,* and Roger W. Cholewiak[2]

Abstract— **Current wearable haptic display technology is limited by the lack of broadband tactors capable of delivering rich haptic effects across the entire perceptible frequency range. Audio speakers are often used in laboratory studies as broadband tactors, but it is difficult to attach them to skin and maintain contact during movement. Commercially-available narrowband tactors are small, low in cost and power efficient. We investigate the idea of interleaving narrowband tactile stimuli to achieve broadband effects. Twelve participants performed pairwise discrimination of two stimulus alternatives using two broadband tactors. One alternative was a broadband vibration composed of the sum of a mid- and a high-frequency vibration, delivered by a single tactor. The other alternative consisted of the mid-frequency component delivered by one tactor and the high-frequency by the other. The upper arm was chosen for stimulation because the tactors can be placed within the two-point limen of the skin. The sensitivity index results were significantly below 1.0, the criterion for discrimination threshold, thereby confirming that broadband haptic effects can be achieved by placing narrowband tactors with mid and high resonant frequencies within the skin's spatial resolution. We provide guidelines and examples of applying our findings to the design of wearable haptic displays.**

I. INTRODUCTION

With the growing interest and development of wearable and array-based tactile displays in both academic research and commercial products, there is a growing need for tactors (tactile actuators) that can be easily attached to the skin at various body sites, and have large ranges of intensity and frequency, preferably independent of one another. Previous studies have employed tactor arrays on hands [1], [2], [3], wrist [4], [5], [6], [7], arm [8], [9], [10], [11], [12], waist [13], [14], [15] and torso [16], [17], [9], [18]. Commercial products include the Optacon for visually impaired (Telesensory Corp., Mountain View, CA), Tactaid VII for hearing impaired (Audiological Engineering Corp., Somerville, MA) and more recent creations for virtual reality and sensory substitution (e.g., TESLASUIT by VR Electronics Ltd., UK; SUBPAC X1 by Subpac Inc. in Palo Alto, CA; Buzz by Neosensory in San Francisco, CA; Hi5 VR Gloves by Noitom in Beijing, China; and Dot Watch by Dot Inc. in South Korea). With few exceptions, the tactors are resonant devices and operate most efficiently only within a narrow, higher-frequency band (>100 Hz), limiting haptic sensations to smooth vibrations. Yet many applications would benefit from stimulus frequencies below 100 Hz to enrich haptic effects for different scenarios. Broadband tactors are desirable for their ability to deliver multiple distinct effects for gaming, virtual reality and sensory substitution.

The mechanoreceptors in human skin can convey distinct sensations such as pressure, slow motion, flutter, roughness and smooth vibration as stimulus frequency increases from <1 Hz to ≈1,000 Hz [19], [20], [21], [22]. Culbertson et al. (2018) used slow (<5 Hz) up-down motions of tactors in an array to simulate stroking on the forearm and succeeded in creating a continuous and pleasant sensation [11]. Shim & Tan (2020) created a 2-by-2 tactor array for the palm and designed vibrotactile signals to capture the essence of natural phenomena such as slow motions at 0.8 Hz for *Breathing*, 20-Hz signals for *Bubbles* and a combination of 30-Hz signals and amplitude-modulated vibrations at 135 and 150 Hz for *Thunder* [23]. The SUBPAC X1 and Razer Nari Ultimate (using the L5 actuator by Lofelt GmbH, Berlin, Germany) have operating frequencies that go down to 35 Hz to convey bass tones in music. With the incorporation of lower frequency components, the expressiveness of tactile effects is greatly enhanced.

There is also strong evidence that higher levels of information transmission can be achieved by employing multi-dimensional tactile stimuli enabled by broadband tactors (see a recent review by Tan et al., 2020 [24]). One example is the TActile Phonemic Sleeve (TAPS) for speech communication on the skin. Reed et al. (2019) describes the encoding of the 39 English phonemes by the 4-by-6 broadband tactor array in TAPS and report a phoneme recognition rate of 86% after one to four hours of learning [12]. A critical factor in their success was the use of mid- and high-frequency signals and amplitude modulation to achieve perceptually-distinct sensations that could be easily learned and memorized. Subsequently, Tan et al. (2020) trained 51 participants with TAPS on the tactile reception of up to 500 English words and demonstrated a learning rate of one word per minute with their best participants [25]. Despite the success of these studies, the broadband tactors employed were relatively large and difficult to attach to the skin, making them only suitable for lab studies, not for wearable applications.

Most mobile devices use either ERM (eccentric rotating mass) or LRA (linear resonant actuator) tactors, while others use solenoids or piezoelectric actuators [26], [27]. LRAs are preferred when signal design calls for independent control of amplitude and frequency. They are high-Q actuators with

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[1] J. S. Martinez, and H. Z. Tan are with the Haptic Interface Research Laboratory, School of Electrical and Computer Engineering, College of Engineering, Purdue University, West Lafayette, IN 47907, USA (e-mail: {`mart1304;hongtan`}`@purdue.edu`).

[2] R. Cholewiak, Sr. Research Psychologist, Emeritus, from the Cutaneous Communication Laboratory at Princeton University, Princeton NJ 08544, USA (email: `rcholewi@gmail.com`).

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peak output over a narrow bandwidth that typically centers around 250 Hz [28], although some are specifically designed with a lower resonant frequency. For example, the rated frequency range of the C2 tactor is 200-300 Hz, while the range for the C2-HDLF is 50-160 Hz (Engineering Acoustics, Orlando, FL, USA). Tactors with lower Q values have much wider bandwidths (e.g., 50-500 Hz for Haptuators by TactileLabs in Montreal, Canada; 35-1000 Hz for Lofelt's L5). They are often larger in form factor, less power efficient and more costly. Given the limited frequency resolution of the skin [29], however, it is questionable whether a tactor has to exhibit continuous frequency response over the entire 0-1000 Hz range to achieve broadband haptic effects.

We propose an alternative way to achieve rich haptic experience using commonly-available tactors. Our approach takes advantage of the limited spatial and spectral resolution of the skin. Except for the hand, the two-point limen is at least 30 mm on the body surface [30], [31]. We hypothesize that two tactors with relatively low and high resonant frequencies, respectively, can be placed sufficiently closely on the skin to mimic one broadband actuator. We performed a psychophysical validation experiment using a pairwise discrimination procedure. Our goal was to assess if the perception of a broadband stimulus is indistinguishable from the perception of two narrowband stimuli delivered in close proximity.

II. METHODS

A. Participants

Twelve participants (6F; 23 to 30 years old) took part in the experiment. All had a normal sense of touch by self report. Two participants (including the first author) also participated in the pilot studies. All signed informed consent forms and received 10 USD as compensation.

B. Apparatus

Two tactors were used (Fig. 1). They were broadband audio speakers (Tectonic Elements, model TEAX13C02-8/RH) with an impedance of 8 Ω across the frequency range of 50-1000 Hz, except for a peak impedance of 35 Ω at ≈600 Hz. Each tactor measures 26.3 mm in diameter (32.2 mm with soldering tab) and 9.0 mm in thickness. A circular adhesive ring on top of the diaphragm provides attachment. It is known that detection thresholds decrease with contactor area until ≈2.9 cm^2 [32]. Therefore, a 3D-printed plastic disk was attached to the adhesive ring to increase the contactor area to ≈3.8 cm^2 (see the white top in Fig. 1). Measurements taken with an accelerometer (Kistler 8794A500) attached to the disk verified that the tactors were able to deliver vibrations without distortion in the frequency range of 10-500 Hz. Tactors were placed side-by-side on a Velcro band without touching (see Fig. 1).

The same tactors were used in the TAPS system for speech communication on the skin [12], [25]. While the tactors work well after calibration in a laboratory setting, they are not suitable for wearable applications due to their large size and the difficulty of maintaining proper contact with the skin during movement.

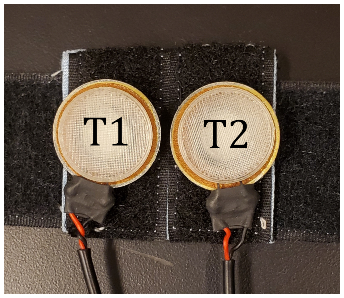


Fig. 1. The two tactors used in the experiment.

The tactors were connected to class D stereo amplifiers (Maxim MAX98306) that received input from a MOTU Ao24 device. The MOTU audio interface performed synchronous D/A conversion of a 2-channel MATLAB waveform played with the Playrec utility [33].

Per additional IRB guidelines for conducting human experiments during the COVID-19 pandemic, a webcam, a microphone and a TeamViewer software were installed to allow the experimenter to control programs and to monitor and communicate with participants from an adjacent room.

C. Experimental Design and Stimuli

The experiment was designed to be a two-alternative, forced-choice (2AFC) paired-comparison paradigm where the participants discriminated between a dual-frequency vibration delivered with one tactor and two single-frequency vibrations delivered with two adjacent tactors. It followed the experimental design of Cholewiak & Collins (2000; Exp. 2) [34] and Cholewiak et al. (2010; Exp. 3) [35]. For the broadband stimulus alternative, one tactor was randomly selected to be driven with the sum of two sinusoidal waveforms, one at a mid frequency and the other at a high frequency. The other tactor was not activated. For the narrowband stimulus alternative, one randomly-selected tactor was driven with a single-frequency vibration at mid frequency, and the other tactor at high frequency.

The pairwise discrimination could be accomplished using any number of perceptual cues including intensity, stimulation site, and spectral masking. Craig & Johnson (2000) described several of these potential confounds that exist in classic psychophysical techniques [36]. Several pilot tests were conducted with two of the participants to rule out irrelevant cues. The stimulus parameters presented below incorporate findings from the pilot tests.

There were four experimental conditions (2 mid frequencies × 2 high frequencies). Lower stimulus frequencies were avoided because the skin is much less sensitive to those, so would require very high signal amplitudes (although see [11]). Our conditions are denoted by the frequency combinations of (30,150), (30,300), (60,150) and (60,300) Hz. We chose 150 Hz and 300 Hz for high-frequency stimuli as they represent the vibration frequencies that can be delivered with most narrowband (resonant-type) tactors and are easily distinguishable from each other. For mid-frequency stimuli, we used frequencies that correspond to rough and fluttery sensations that feel distinct from the smooth, and sometimes penetrating, high-frequency vibrations. It is well documented that two different sets of peripheral fibers mediate vibrations in the mid frequency range of 10-60 Hz and high frequency range of 100-400 Hz, respectively, overlapping in the 60-100 Hz range [20], [21]. Psychophysical studies provided further evidence that these two frequency ranges are perceptually distinct and remain so when combined [37] [38] [22]. The signals were 400 ms in duration and smoothed by a 5-ms Hanning window so they started and ended at zero amplitude.

Intensity equalization was a major challenge because any discernible difference in perceived intensity could serve as a perceptual cue for the pairwise comparison. The intensity of the high-frequency components was set to 13 dB SL (sensation level; dB above detection threshold at the respective frequency). Based on Bolanowski et al. (1994), amplitudes corresponding to 13 dB SL at 150 and 300 Hz are below the detection thresholds of non-Pacinian receptors (nPC) at 30 and 60 Hz on hairy skin [39], ensuring no masking of mid-frequency components by high-frequency vibrations (see further explanation in Gescheider et al., 1982 [40]). However, since the detection thresholds at 30 and 60 Hz are higher than those at 150 and 300 Hz [39], it was impossible to choose a signal amplitude at the mid frequencies that would not also activate the Pacinian channel (PC). Although most masking studies use high-frequency components as maskers, Verrillo et al. (1983) showed evidence of a 13-Hz nPC stimulus masking a 300-Hz PC stimulus at the fingertip [41], but only when the intensity of the 13 Hz stimulus exceeded the threshold for PCs at 13 Hz. Therefore, in the present study, the levels of the mid-frequency components were adjusted by the participants using a matching procedure to account for possible masking effects at high frequencies by mid-frequency vibrations (see Sec. II-D.3). While the choice of displacement levels described above served the aim of the present research, it should not be viewed as a limitation on the intensity range that can be used in practical applications.

Another consideration was choosing a body site where the two tactors could be placed within the spatial discrimination threshold, to eliminate tactor localization as a perceptual cue. The tactors needed a minimum center-to-center distance of $\approx$30 mm to avoid direct contact. While this was below the 40 mm two-point limen for touch on the forearm reported by Weber (1834) [30] and Weinstein (1968) [31], Mancini et al. (2014) reported a two-point discrimination threshold of 22 mm on the forearm [42]. On the upper arm, the two-point limen is reported to be 44 mm and 67 mm by Weinstein (1968) [31] and Weber (1834) [30], respectively, both of which are well above 30 mm. It was also important to avoid any perceptual anchors such as the elbow that can be easily localized (see Cholewiak & Collins (2003) [8]) and to avoid bone conduction that might elicit auditory sensations. Therefore, the fleshy surface atop the biceps on the left upper arm was chosen to be the stimulation site.

Fig. 2. Participant wearing the tactor band on top of the left biceps. The computer screen shows the interface for pairwise discrimination. Button “A” is associated with the broadband, single-tactor stimulus and button “B” with the narrowband, two-tactor stimulus.

D. Procedure

The participant wore a thin fabric sleeve on the left arm for hygiene purpose. The experimenter wrapped the tactor band around the participant’s left upper arm and fastened it with Velcro so that the two tactors were on top of the biceps (see Fig. 2). The experimenter then left the room and controlled the computer remotely while on a video conference call with the participant. The participant sat facing the computer screen with the left arm resting comfortably on a table and the elbow supported. The participant was instructed to avoid flexing or moving their left arm during the experiment. Audio pink noise was played through a headset throughout the experiment to mask any audible noise from the apparatus.

There were four experimental stages: Threshold measurement, tactor equalization, intensity matching, and pairwise discrimination. The participant could take a 5-min break between stages if needed. It took 1 hour for each participant to complete the four stages in a single session.

1) Threshold Measurement: Detection thresholds were measured for each participant at the beginning of the session. Thresholds were measured at the four test frequencies using tactor T2 which was closer to the torso. A three-interval, two-alternative, forced-choice, one-up two-down adaptive procedure with trial-by-trial response feedback was employed. The one-up two-down rule estimates the 70.7-percentile point for signal detection [43]. The vibration amplitude was adjusted with a step size of 5 dB for the first 4 reversals, and 2 dB for an additional 12 reversals. In a trial, the 400-ms signal was presented in only one of the three intervals, with equal *a priori* probability. Each interval was visually indicated and the inter-signal interval was 500 ms. The participant indicated which interval contained the signal and received feedback for that trial. The threshold was estimated as the mean of the last twelve reversals at the smaller step size.

2) Tactor Equalization: Participants then completed a method of adjustment procedure to equalize the perceived intensity of the two tactors. A 400-ms long signal at 300 Hz and -10 dB (relative to the maximum output allowed by the MATLAB software) was delivered to T2, the reference tactor. The participant adjusted the amplitude of a 400-ms, 300-Hz signal on the test tactor T1 until the two were perceived to be equally strong. The tactors were activated in the sequence reference-test-reference and the participant increased or decreased the intensity of the test tactor in steps of 1 dB. The final adjustment was recorded.

The results of threshold measurement and tactor equalization were used to calculate signal amplitudes at 150 and 300 Hz that corresponded to 13 dB SL. The two stages ensured that the participants received vibrations at the same perceived intensity levels despite individual differences in detection thresholds and possible differences between the two tactors.

3) Intensity Matching: Participants then completed a matching procedure to calibrate the amplitudes of mid frequencies for each of the four experimental conditions. For each frequency combination, the broadband dual-frequency stimulus (the reference) used 13 dB SL for both the mid- and high-frequency amplitudes. For the two single-frequency stimulus alternatives (the comparison), the high-frequency amplitude was also 13 dB SL. The amplitude of the mid-frequency component could be changed by the participant using the method of adjustment [44]. The participant felt a sequence of three signals in the order reference-comparison-reference, and adjusted the amplitude of the mid-frequency component until the comparison stimulus felt similar to the reference. The results indicated that the adjusted values for the mid-frequency component were not significantly different from 13 dB SL for the four conditions.

4) Pairwise Discrimination: For the discrimination experiment itself, a series of one-interval, two-alternative, forced-choice (1I-2AFC) trials with response feedback was conducted. The order of the four experimental conditions was randomized for each participant. At the beginning of each condition, the two stimulus alternatives were presented once to the participant. This was followed by a block of 60 trials with the first 10 trials considered as training and discarded from data analysis. On each trial, one of the two stimulus alternatives was presented with equal *a priori* probability. The participant felt the stimulus and responded by clicking one of two buttons on the computer screen. A check mark appeared above the selection for a correct response. For an incorrect response, a cross appeared above the incorrectly selected button and a check mark was shown above the correct button. The trial-by-trial feedback helped the participants to attend to the relevant sensations. Participants were allowed to take a break at the end of each block of trials, and continued to the next block by clicking on a "Next" button when ready.

E. Data Analysis

The results of the 1I-2AFC discrimination experiment were analyzed using a decision model from Signal Detection Theory [45]. It is assumed that participants discriminated the two stimulus alternatives by comparing the percept, modeled as a random variable x called the "decision variable", with a predetermined criterion. The two conditional probability density functions of x follow two Gaussian functions of the same variance but different means for the two stimulus alternatives. Based on the hit rate H and false-alarm rate F, two performance measures can be computed. The sensitivity index d′ is the normalized distance between the means of the two Gaussian distributions. It provides a measure of the participant's sensitivity to the difference between the two stimuli, and is not confounded by response bias. A d′ value below 1.0 indicates that the two stimulus alternatives cannot be discriminated reliably. The response bias β is the normalized distance between the average of the means of the two Gaussian distributions and the response criterion. A β value near 0.0 indicates low bias in a participant's decision to choose one of the two responses in a discrimination task. When $\beta = 0.0$, d′ $= 0.0$ and 1.0 correspond to 50% and 69% correct, respectively.

After a z transform of the hit and false-alarm rates using the following equation,

$$H = \int_{-\infty}^{z(H)} \frac{1}{\sqrt{2\pi}}\, e^{-\frac{x^2}{2}}\, dx, \quad F = \int_{-\infty}^{z(F)} \frac{1}{\sqrt{2\pi}}\, e^{-\frac{x^2}{2}}\, dx. \tag{1}$$

The value of d′ is calculated as the difference between the two z scores and β is the negative average of the z scores:

$$d' = z(H) - z(F), \quad \beta = -\frac{1}{2}[z(H) + z(F)]. \tag{2}$$

When the hit rate is 1.0 or false-alarm rate is 0.0, d′ becomes infinite. In such a case, the corresponding values are adjusted to be $1.0 - 1/(2N)$ or $1/(2N)$, respectively, where N is the total number of times a stimulus alternative is presented [46, Chapter 1].

III. RESULTS

The intensity matching results are presented as box plots in Fig. 3. The distributions of the adjusted amplitudes of the single-frequency vibrations at the mid frequencies are shown for the four experimental conditions. They are compared to the 13 dB SL amplitude level used with both components of the dual-frequency stimuli and the high-frequency components of single-frequency stimuli. There appears to be a wide range of the adjusted amplitudes with some outliers at conditions (30,300) and (60,300). However, a one-way ANOVA did not indicate a significant effect of experimental condition ($F(2, 44) = 1.02, p = 0.39$). Furthermore, individual t-tests per condition did not show a significant difference between the adjusted amplitudes and 13 dB SL [$t(11) = -1.79, p = 0.10$ for condition $(30, 150)$; $t(11) = -1.58, p = 0.14$ for $(30, 300)$; $t(11) = -0.88, p = 0.39$ for $(60, 150)$; $t(11) = -0.05, p = 0.96$ for $(60, 300)$]. The variability of the data shown in Fig. 3 suggests that the intensity matching stage was necessary.

The d′ results from pairwise discrimination are shown in Fig. 4. The four d′ values for the four experimental conditions were all between 0 and 1, indicating that the participants could not reliably distinguish between a dual-frequency vibration delivered by one tactor and two corresponding single-frequency vibrations delivered by two adjacent tactors. Individual t-tests per condition confirmed that all d′ values were significantly below 1.0 [$t(11) = -4.62$ for condition

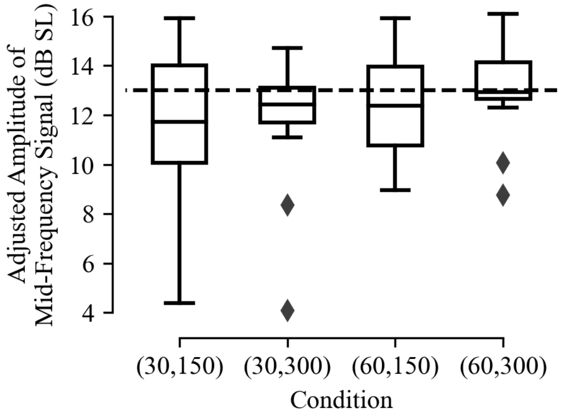


Fig. 3. Results of adjusted mid-frequency amplitudes from intensity matching. The horizontal dashed line corresponds to 13 dB SL.

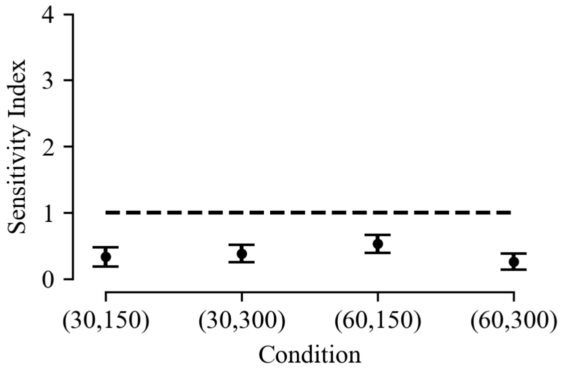
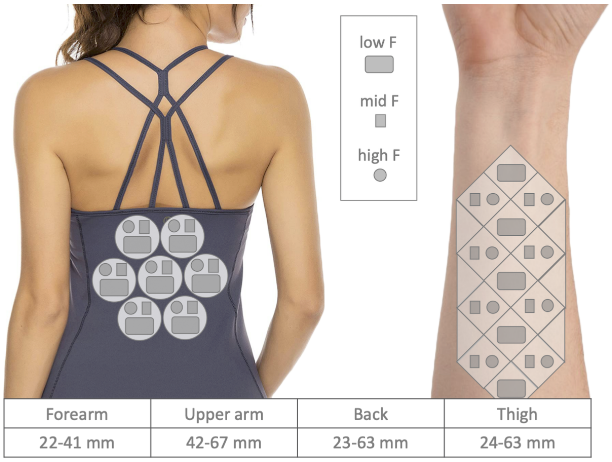


Fig. 4. Results of sensitivity index d′ from pairwise discrimination. The dashed horizontal line indicates d′=1.0. Error bars denote ± 1 std.err.

$(30,150)$; $t(11) = -4.80$ for $(30,300)$; $t(11) = -3.46$ for $(60,150)$; $t(11) = -5.88$ for $(60,300)$; all with $p < 0.01$]. A one-way ANOVA test indicated no significant difference among the d′ values across the four conditions ($F(3,44) = 0.73, p = 0.54$). The response biases, β, were relatively small, ranging from -0.16 to -0.04 for the four conditions.

IV. Guidelines for Interleaving Narrowband Tactile Stimuli for Broadband Effects

Our finding that the d′ values under all experimental conditions were well below 1.0 provides psychophysical validation that broadband haptic effects can be achieved by interleaving narrowband vibrotactile stimuli, when narrowband tactors are placed within the two-point limen on the skin. A body site can be divided into distinct stimulation areas defined by the two-point limen, as illustrated by the circular grid on the back and the diamond grid on the forearm in Fig. 5. The exact shape of the grid element is not important, as long as (i) tactors within each area are felt as one location and (ii) tactors in different areas are felt as two locations.



Forearm	Upper arm	Back	Thigh
22-41 mm	42-67 mm	23-63 mm	24-63 mm

Fig. 5. Illustration of interleaving narrowband tactors in a wearable haptic display worn on the back or volar forearm. The large circles on the back and the diamonds on the forearm indicate spatially distinct areas of stimulation. The legend shows the three types of narrowband tactors. The table at the bottom lists the two-point limens at select body sites (from [30], [31], [42]).

The question arises as to how many narrowband tactors should be placed within each distinct area of stimulation. Single-frequency sinusoidal stimulation over the entire vibrotactile frequency range of 0-1000 Hz elicit three distinct sensations: pressure variation / slow motion at low frequency (up to ≈6 Hz), fluttery (with low amplitude) / rough (with high amplitude) at mid frequency (≈10-70 Hz) and smooth vibration at high frequency (above 100 Hz). Furthermore, vibrations from the three frequency ranges can be combined and remain salient perceptually. For example, a dual-frequency vibration with 30 and 300-Hz components feel like a smooth vibration (due to 300 Hz) with superimposed roughness (due to 30 Hz) [22]. Therefore, up to three narrowband tactors can be placed within each area with each tactor operating over the low-, mid- or high-frequency range, respectively. The left panel in Fig. 5 provides an example of a haptic back display with three types of tactors in each distinct stimulation area. The right panel shows one variant where low-frequency tactors are placed along the middle of the forearm to deliver, for example, pleasant strokings using the signal patterns described in Culbertson et al. (2018) [11]. The rest of the grid contains two parallel columns of mid- and high-frequency tactors that can be used to encode English phonemes using haptic codes similar to those in Reed et al. (2019) [12]. Such wearable displays can differ in many ways including body sited stimulated, layout of distinct stimulation areas, number and type of tactors within each stimulation area, waveforms and signal activation patterns.

In conclusion, we propose, test and validate a new way of achieving rich, broadband haptic effects by interleaving narrowband vibrotactile stimuli on the skin. We provide guidelines and examples of applying this approach in creating new wearable consumer products. Whereas the present study used a relatively large broadband tactor, most commonly-used tactors are smaller in size (e.g., a footprint of 1 cm × 1 cm or less in mobile phones). It is therefore possible to place one mid-frequency and one high-frequency resonant tactors within the two-point limen on the skin using tactors that are commercially available today. Our work also contributes to future development of tactors by providing perception-based specifications on frequency range and tactor dimensions.

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