Perceptual Dimensions of Vibrotactile Actuators*

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***Abstract*— The objective of the present research was to determine how variations in the signals generated by different vibrotactile actuators are perceived and which features are judged as being distinctive. For this purpose three different types of actuator were used to generate signals that varied in amplitude, waveform and frequency. Participants were required to judge the degree of similarity-dissimilarity between pairs of stimuli and multi-dimensional scaling (MDS) techniques were then used as an exploratory data analysis technique to create a spatial map that depicted the relations among the various vibrotactile signals. The first dimension that emerged from the MDS represented a continuum associated with transitions in the amplitudes of the signals, with a smooth sine wave pattern contrasting with the more abrupt transitions in square waves. This may be considered a smooth-rough dimension. The second dimension extracted from the data was more difficult to characterize in that each of the two clusters along this dimension involved signals of varying waveform and frequency. Further work will aim at defining the perceptual qualities of this dimension.**

I. Introduction

Tactile displays encompass a spectrum of devices ranging from those affixed to steering wheels in vehicles that provide spatial or warning cues about the environment [1-3], to more dense arrays used to present tactile cues to the fingertips, such as virtual or refreshable Braille displays [4], [5]. At present, most tactile displays deliver simple vibrotactile inputs at single frequencies that are within the range of maximal sensitivity of the skin (i.e. 100 Hz-300 Hz). Devices have also been developed that use electrotactile and electrostatic inputs [6], [7] to stimulate the skin. The predominance of displays based on vibrating motors reflects the fewer safety and comfort considerations associated with their use and the larger dynamic range of stimulus parameters available to communicate information when compared to electrotactile displays.

Tactile displays can provide either static inputs such as refreshable Braille displays in which round-tipped pins indent the skin [5] or dynamic signals such as the vibrations implemented in many consumer devices [8], [9]. The advantages of vibrotactile signals are that they vary along several dimensions namely frequency, waveform, intensity, and duration each of which can be used to create a range of inputs [10]. Such tactile stimuli are often referred to as tactons and represent the basic element of a tactile communication system [11-14]. Psychophysical studies provide a framework that assists in determining which stimulus dimensions and ranges of values are effective for designing tactons [15], [16]. To date, variations in the temporal profile of stimuli and the location on the body stimulated have been used most frequently to generate different tactile patterns [17]. The selection of these two parameters reflects the skin's sensitivity to changes in the temporal properties of stimuli, which is inferior to that of the ear but superior to the eye [18], and its capacity to encode the spatial coordinates of tactile stimulation accurately [19].

There are challenges associated with using some of the other dimensions of vibrotactile signals to create tactile patterns. For example, variations in waveform are not readily distinguished at higher frequencies [20], and the frequency and amplitude of vibration are not orthogonal perceptually, which means that when one changes, such as the frequency of vibration, so too does the other, namely its perceived amplitude [21], [22]. The perceived frequency of a constant vibration signal also varies at different locations on the body. In regions with higher densities of mechanoreceptors, such as the fingertips, perceived frequency increases more rapidly with increasing frequency than in areas with lower innervation densities such as the forearm [23], [24]. This means that the same vibro- tactile stimulus may be perceived differently when presented on a device attached at different locations on the skin.

Much of the research on designing tactons has been empirical and focused on identifying which properties of vibrotactile stimuli are attended to and interpreted intuitively. These studies have often been performed with a specific type of actuator, such as the C2 tactor (Engineering Acoustics, Inc) [25], [26], which has made it difficult to generalize findings across studies in which smaller, less robust actuators have been used (e.g. [27], [28]). The results from numerous experiments using different types of actuators have indicated that when pulse duration and inter-pulse interval are varied, the cadence or rhythm of the tactile signal is perceived. This is readily encoded as representing features such as an object's proximity, or the urgency of an incoming signal or an impending event [29], [30].

In addition to temporal properties, spatial cues about the environment can be conveyed very effectively using an array of vibrating motors mounted on the body. When specific motors in the array are activated individually or sequentially the user's attention can be directed to a particular spatial location or the tactile cue can indicate the intended direction of movement [17], [31-33]. It seems to be intuitive to interpret an external direction emanating from a single point of stimulation on the body. A further perceptual dimension emerges when the properties of a vibrotactile waveform vary through time. When the amplitude of a base signal such as a 250 Hz sinusoid is modulated by a second sinusoid, the

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perceived roughness of the resulting waveform changes as the modulating frequency decreases from 50 to 20 Hz [14]. The creation of tactile textures based on waveform modulation provides a further dimension for use in tactile communication systems.

A further avenue that has been explored for developing tactons is the creation of vibrotactile libraries [26]. Immersion Corporation's Haptic Layer Library and Haptic Muse were designed for developers who are interested in implementing tactile effects in their gaming applications [34]. Disney Research's Feel Effects has been designed to enhance the interactions of users with a variety of media content such as stories and movies [35]. Each library has an organizational principle that is used to cluster the effects based on sensations (e.g. roughness) or associated metaphors (e.g. rain). Several approaches have been adopted in developing these libraries including mapping vibrotactile effects onto specific verbal descriptions, such as the feel of heavy rain or a stick poking at someone [35].

Much of the focus of research on vibrotactile libraries has been to relate tactile cues to verbal identifiers or descriptions of experiences, with the idea of developing a general mapping algorithm that relates the physical stimulus to a semantic connotation. In these applications the tactile effects have meaning due to their association with visual and auditory inputs and so the design goal is fundamentally different from that used to develop tactons. In the latter case, the tactile effects are supposed to have intrinsic meaning and do not rely on other sensory inputs for interpretation. Nevertheless, some of the organizational principles used to create vibrotactile libraries for gaming applications and digital media are relevant to the development of tactile signal libraries.

A further dimension of tactile displays that could be used as an element in creating tactons or vibrotactile libraries is the specific mechanical input delivered by different actuators. Different actuator technologies have been used to create tactile displays, including eccentric rotating mass (ERM) motors, linear resonant actuators (LRA), voice coil motors, piezoelectric actuators, and electroactive polymer actuators [25], [36], [37]. Variations in the mechanical signals generated by these various actuators could be exploited in designing multi-actuator tactile displays to provide inputs that are perceptually distinct and so readily recognized by users. Specific types of information, such as a subtle pressure cue delivered by an actuator with a limited bandwidth may be used to signal the passage of time, whereas a high frequency vibratory input could indicate a sense of urgency.

The objective of the present research was to determine how variations in the signals generated by different vibrotactile actuators are perceived and which features are judged as being distinctive. For this purpose three different types of actuator were used to generate signals that varied in amplitude, waveform and frequency. Participants were required to judge the degree of similarity-dissimilarity between pairs of stimuli and multi-dimensional scaling (MDS) techniques were then used to determine the perceptual relations among these stimuli. It is anticipated that the MDS analysis will provide an indication of the most salient variables that people use to group vibrotactile signals. MDS has been used successfully to understand the perceptual dimensions of tactile textures [38-40], and haptic icons [30], [41].

II. Experimental Design

A. *Participants*

Ten normal healthy individuals ranging in age from 24 to 29 years (mean 27 years) participated in the experiment. They were all right-handed and had no known abnormalities of the peripheral sensory or vascular systems. None of the participants had any significant experience in tactile perceptual studies. They all signed an informed consent form that was approved by the MIT Committee on the Use of Humans as Experimental Subjects.

B. *Apparatus*

Three vibrotactile actuators (tactors) were selected for the experiment: the EMR tactor (Engineering Acoustics, Casselberry, FL, USA), the C3 tactor (Engineering Acoustics, Casselberry, FL, USA) and the Haptuator Mark II (Tactile Labs, Montreal, Canada). The EMR tactor is based on an eccentric mass motor mounted within a suspension. The rotation of the eccentric mass results in an off-axis load on the contactor on the skin and the suspension restricts the lateral compliance of the motor mass. The vibration signal delivered is primarily perpendicular to the skin. The C3 tactor is a small linear moving-magnet actuator with a moving contactor that is lightly preloaded against the skin. When activated the contactor oscillates perpendicular to the skin while the surrounding area is shielded by passive housing. The Haptuator Mark II is an ungrounded moving magnet voice-coil type linear actuator with a cylindrical magnet suspended by two rubber membranes. The three actuators were each mounted in an identical enclosure (see Fig.1) to ensure that the contact conditions for each tactor on the skin were the same. The enclosures also guaranteed there were no visual or extraneous tactile cues that made the tactors distinguishable. The dimensions and specifications of the actuators are provided in Table 1. The three tactors vary with respect to their operating principle and optimum frequency.

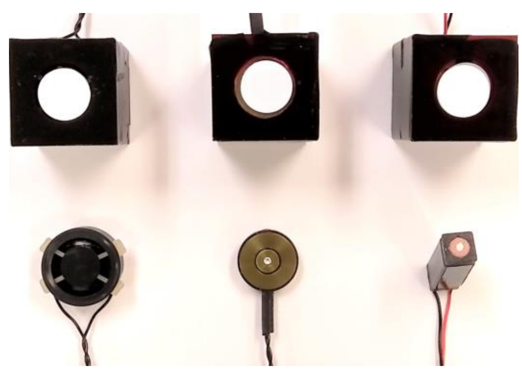

Fig. 1 The three tactors from left to right: EMR, C3 and Haptuator Mark II. The enclosures within which each tactor was mounted are shown on top.

The performance of each of the actuators was first characterized by varying the input to the motor and measuring its response as the frequency, amplitude and waveform of the input was varied. On the basis of these preliminary studies the range of inputs that could be presented across the three motors was determined. The objective of these pilot studies was not to create signals that were identical but to have a set of stimuli that had similar properties so that they could be compared perceptually.

TABLE 1. PROPERTIES OF VIBROTACTILE ACTUATORS

Specifications	EMR tactor	C3 tactor	Haptuator II
Dimensions*	25.4 x 10.2 mm	20.3 x 6.35 mm	9 x 9 x 32 mm
Weight	5 gm	8 gm	9.5 gm
Operating freq.	80-140 Hz	180-320 Hz	90-1000 Hz
Optimum freq.	115 Hz	240 Hz	120 Hz
Peak-to-peak displacement	1.3 mm	0.55 mm	7.5 G

* The EMR and C3 tactors are round, dimensions are diameter x height; the Haptuator is oblong with dimensions of the square cross section and length.

C. Vibrotactile Stimuli

The three dimensions selected to create vibrotactile signals were waveform (triangular, square or sinusoidal) frequency (15, 20 or 30 Hz) and intensity. The particular stimulus parameters were selected based on their perceptibility as other parameters were varied. For the EMR tactor there was no perceptible difference between a square wave and a triangular wave input, they both felt sharp in comparison to the smooth sinusoidal input and could not be distinguished. At low frequencies the triangular wave and square wave signals were discriminable when presented on the C3 tactor and Haptuator and were clearly different from the sinusoidal input. For these two tactors, three waveforms were therefore implemented, whereas only two waveforms were used with the EMR tactor.

TABLE 2. CHARACTERISTICS OF VIBROTACTILE STIMULI

Motor	ID	Pattern	Stimulus	Waveform	Intensity	Freq.
Haptuator Mark II	HAP	1	HAP-1	Square	100 mV	20
		2	HAP-2	Sine		15
		3	HAP-3	Triangle		30
C3 Tactor	C3T	1	C3T-1	Square	800 mV	20
		2	C3T-2	Sine		20
		3	C3T-3	Triangle		30
EMR Tactor	EMR	1	EMR-1	Square	800 mV	20
		2	EMR-2	Sine		15

The characteristics of the vibrotactile signals are described in Table 2 and illustrated in Fig. 2. The range of frequencies was determined based on the perceptibility of the waveforms at varying frequencies. As the frequency increased above 25-30 Hz on all three tactors it became very difficult to distinguish between the waveforms of the signals, they all felt like a constant buzzing. The intensity of the signal output by the Haptuator was set to a level that was comparable to that of the other two tactors.

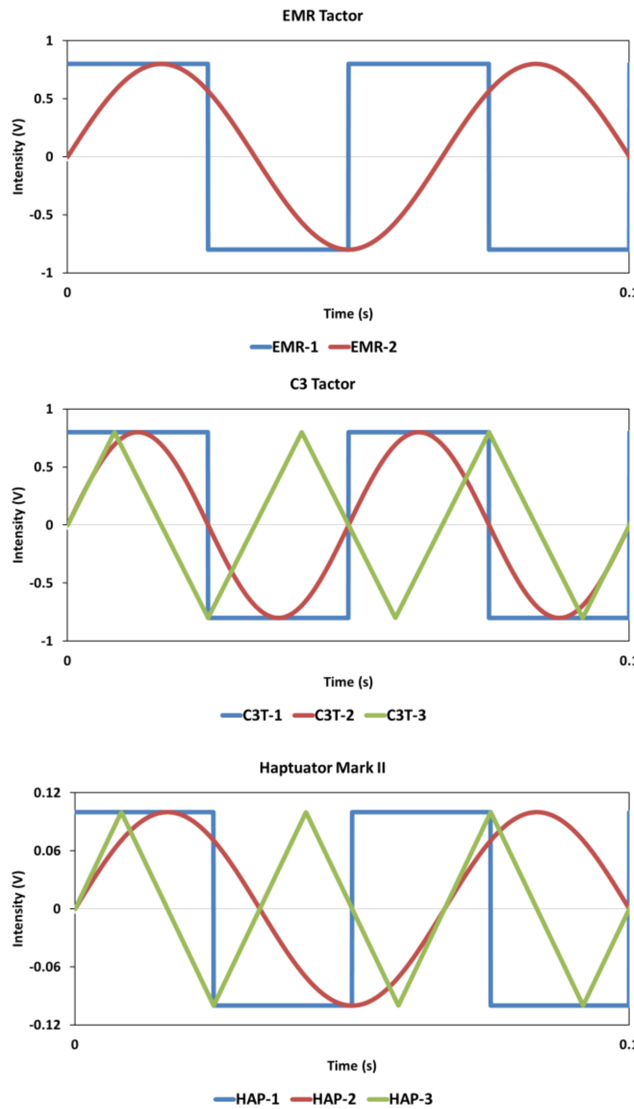

Fig. 2. The vibrotactile signals produced by each of the three actuators illustrating the variations in waveform, intensity and frequency.

D. Procedure

On each trial participants placed their index fingers on top of the fixtures enclosing the tactors as shown schematically in Fig. 3. They were told that they would feel a vibration signal on each fingertip and that they were to determine how similar the two signals were. They were instructed to give their responses based on their overall perception of the signal and not on any particular parameter of the vibrotactile stimulus. Each trial lasted for 4 seconds. At the end of each trial an auditory cue signaled that participants should indicate their response based on the degree of similarity between the two stimuli presented. They recorded their response on a GUI displayed on a computer screen in front of them. They moved a cursor to indicate the degree of similarity they perceived between the stimuli on a scale from 0 (not at all similar) to 30 (exactly similar). The responses had to be made within 10 seconds and on most trials participants made their responses within a couple of seconds. Once the response was made, participants placed their index fingers back on the fixtures for the next trial. For the three tactors and range of stimuli presented on each tactor, a total of 28 pairs of stimuli could be compared. Each stimulus pair was presented three times giving 84 trials, with the order of presentation being randomized. Prior to starting the experiment participants were familiarized with the vibrotactile stimuli that were to be presented.

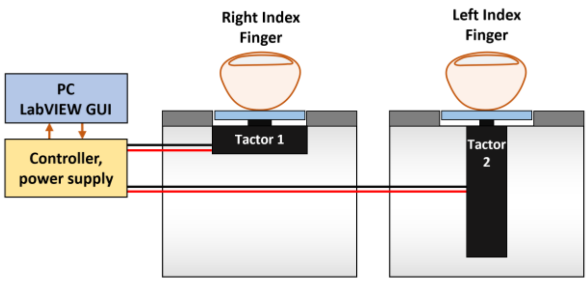

Fig. 3. Schematic illustration of the position of the fingertips on the tactors during the experiment.

III. Results

The participants' responses made on the GUI on each trial were saved in the form of a series of PNG images which were then digitized using the Image Processing Toolbox in MATLAB (Mathworks, Inc.). The data were then averaged across trials and participants for the eight stimuli to create a square symmetric distance matrix to perform the MDS analysis. This was done using SPSS (IBM Analytics).

The objective of the MDS analysis is to obtain the best fit with the smallest number of dimensions. This can be assessed using the scree plot which is shown for the experimental data in Fig. 4 where the stress function value is plotted against the dimension number. A distinct elbow is not evident in the plot. The elbow is usually interpreted as indicating that increasing dimensions beyond the point at which it occurs does not affect the stress in any significant manner. It is possible that a larger stimulus set with more observations would enable more dimensions to be extracted, although it should be noted that distinctive elbows are relatively rare [38], [39].

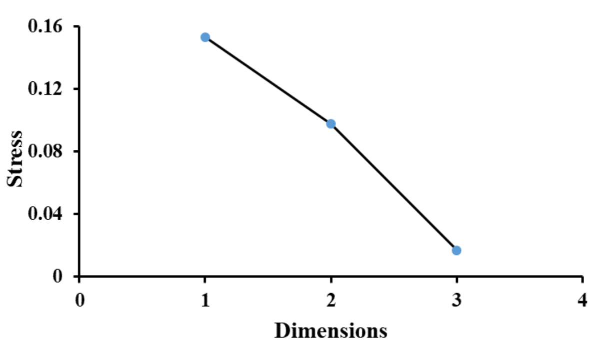

Fig. 4. Scree plot with stress function value plotted against dimension number.

The MDS solution with two dimensions for the eight stimuli presented is illustrated in Fig. 5. Two dimensions seems to be the most parsimonious interpretation of these results, given the stimulus set size. It is evident that some stimuli are clustered closely together such as HAP1 and EMR1, which are both 20-Hz square waves, and are perceptually similar to the 30-Hz square wave delivered by the C3T. These three stimuli form one end of a dimension with two of the sine wave stimuli (HAP2 and C3T2) clustering at the other end. For this first dimension the perceptual distinctiveness associated with varying waveform, with a smoother sine wave pattern contrasted with the more abrupt transitions in square waves, suggests a smooth to rough continuum. The second dimension groups the 30-Hz triangular wave inputs on the C3T and EMR tactors with the 15-Hz sine wave on the EMR tactor, and at the other end of the dimension the 15-Hz sine wave on the Haptuator and 20-Hz square wave on the C3 tactor are clustered. Despite the similarities in the frequencies and waveforms of these stimuli, they are clearly grouped perceptually based on other emergent properties that render them distinct.

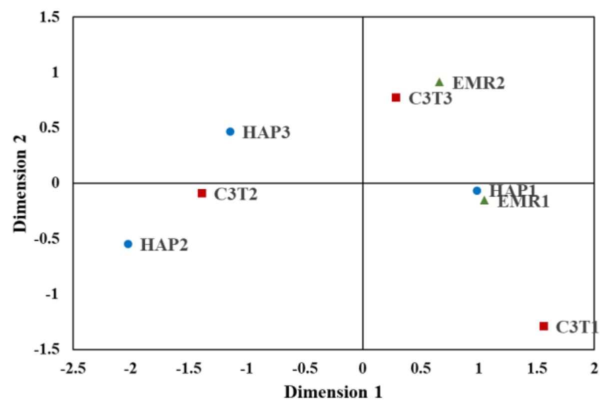

Fig. 5. Two-dimensional MDS configuration.

IV. Discussion

MDS was used as an exploratory data analysis technique to create a spatial map that depicted the relations among the various vibrotactile signals implemented on different actuators. The perceived distances between the vibrotactile stimuli presented were placed in a Euclidean space of three dimensions with the inter-stimulus distance reflecting the dissimilarities. The relatively small number of stimuli implemented on the tactors and number of judgments made for each stimulus meant that it was appropriate to limit the interpretation of the results to only two dimensions. Due to the physical constraints associated with presenting the stimuli on each trial which involved moving the encased actuators into a fixture under the fingertips, direct comparisons between pairs of stimuli seemed the most efficient method of obtaining judgments. A similar method was used by Grey [42] in his seminal work on the scaling of musical timbres. In haptic research, MDS tasks have typically involved grouping or sorting in which a relatively large set of textures or haptic icons is grouped into clusters [38-41]. The number of dimensions emerging for these perceptual tasks has ranged from two to four.

The underlying dimensions extracted from the spatial configuration of the data in the present experiment reflect a sensitivity to the spectral content of the signals. At the low frequencies implemented (15-30 Hz), participants grouped the stimuli along one dimension that perceptually went from "rougher" waveforms with abrupt amplitude transitions to smoother signals with more gradual transitions in amplitude. Previous research which had suggested that people are relatively insensitive to different vibrotactile waveforms had used much higher frequencies (100-400 Hz) [20], which we had also noted in our preliminary experiments made variations in waveform difficult to distinguish. The compromise in the present study was to focus on varying the waveform of the signals at the cost of keeping the frequencies relatively low. The sensitivity of participants to stimulus waveform suggests that at low frequencies this may be a useful dimension for tactile communication systems. The second dimension extracted from the data is more difficult to characterize in that each of the two clusters involves signals of varying waveform and frequency. It is possible that there are features of the mechanical input delivered by a particular tactor in contact with the skin that make it seem more distinct or similar to the signals delivered by the other tactors. This needs to be determined experimentally by recording the displacement of the skin during stimulation.

Previous work in which MDS techniques have been used to aid the design of haptic icons with one specific actuator [30], [41], used waveform, frequency and force amplitude as the three primitives. For that stimulus set and sorting task, frequency which varied from 0.5 to 100 Hz was determined to be the strongest grouping variable, with waveform being the next most important [41]. In a further experiment when the frequency range was limited to between 3 and 25 Hz, it no longer dominated how participants grouped haptic stimuli. This clearly indicates that the specific range of values implemented for any parameter in a stimulus set can have a profound effect on perceptual distinctiveness.

The actuators selected for the present experiment varied with respect to their bandwidth, response times, and capacity to generate different waveform profiles [25]. They are similar to many of the actuators used in research on tactile communication systems [10] [14], but are sufficiently different that perceptually distinct signals could be generated. The mechanical inputs delivered by these motors depend on the design of the moving element or probe that makes contact with the skin. In voice-coil motors such as the Haptuator, displacement is produced in a plane normal to the skin surface, whereas with the EMR motor there is motion normal and parallel to the skin surface [25], [43]. Each of the tactors was encased in an identical enclosure so that the surface area and the compliance between the skin and the moving element in contact with the skin did not vary substantially across actuators. The vibration signals generated by each of the tactors would nonetheless still vary as a function of the motor's operating principle. Despite these differences the perceptual dimensions that emerged from the MDS were not defined by the specific actuator presenting the stimulus, which suggests for these motors they can be used interchangeably within the parameter set used. The Haptuator is capable of producing much stronger inputs than the other two actuators and so the intensity of this tactor was adjusted to be similar to that of the other two tactors. With a more robust input the distinctiveness of the Haptuator is more evident and that may become a factor in judging the similarity of different vibrotactile signals.

In this initial experiment a relatively small stimulus set was used to evaluate the perceptual dimensions that emerge when different vibrotactile actuators deliver signals to the skin. The MDS analysis revealed that participants respond to the transitions in amplitude of the displacement on the skin in what may be characterized as a smoothness/roughness dimension. A second dimension emerged that is more difficult to characterize but that does not simply reflect variations in the frequency or waveform of the vibrotactile stimuli. Further work with a larger stimulus set will attempt to define more precisely the perceptual quality of this dimension.

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