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Interaction of perceived frequency and intensity in fingertip electrotactile stimulation: Dissimilarity ratings and multidimensional scaling

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Abstract

Sensations elicited by electrical stimulation of touch are multidimensional, varying in perceived intensity and quality in response to changes in stimulus current or waveform timing. This study manipulated both current and frequency while volunteer participants estimated the dissimilarity of all non-identical pairs of 16 stimulus conditions. Multidimensional scaling analysis revealed that a model having two perceptual dimensions was adequate in representing the electrotactile (electrocutaneous) sensations. The two dimensions were identified as perceptual frequency and intensity, and were strongly correlated with the two stimulus variables, frequency and current, although not in a 1:1 correspondence. Perception of frequency differences increased monotonically with stimulus intensity, which is consistent with other human sensory systems such as hearing and vision. Our results are consistent with previously-reported research using different methodology and cutaneous locus. Congruence across different methods and laboratories suggests similar underlying perceptual mechanisms.

INTRODUCTION

Electrical excitation of cutaneous afferent nerves via surface electrodes produces localized tactile (touch) sensations that vary in perceived intensity and quality depending on the variables of stimulation: current, frequency, pulse timing and burst structure, electrode geometry, and skin locus and condition (e.g. hydration). This controllability leads to the use of electrotactile stimulation as an alternative data channel to provide its user with information normally communicated through a different sense [1, 2]. Applications of sensory substitution include sensory prostheses for persons with serious visual [3-6], auditory [7, 8], and balance [9] impairments, as well as for those who have lost tactile sensation on some cutaneous loci (e.g. insensate hand or feet) due to traumatic nerve injury or disease [10], for feedback during advanced robotic surgical techniques [11], and potentially for virtual environment applications [12, 13]. Some electrotactile technologies are currently being commercialized[1].

Efficient information coding for potential applications requires knowledge of the perceptual dimensions resulting from changes in the electrotactile stimulus variables and their interactions. Regardless of sensory domain, there is not necessarily a 1:1 correspondence of stimulus to perceptual dimensionality. For example, varying *either* the frequency *or* sound pressure level of a pure auditory tone may result in perceived changes in both pitch and loudness [14]. Visual hue and brightness similarly interact in response to stimulus wavelength and illumination [15, 16].

Electrotactile stimulation results in a wide variety of perceived sensations (percepts) described as tingle, vibration, pressure, pulsation, fizz, pinprick, and buzz depending on the stimulus variables [17, 18]. literature, considerable attention has been devoted to the intensive perceptual attributes, including psychometric, magnitude growth, and matching functions [19-23]. Quality of sensation has received less attention [17, 24], although this is particularly important because electrotactile and mechanical stimuli can feel quite different due to different activation patterns of the primary tactile and nociceptive afferent nerve fibers [25]. To this end theoretical and practical efforts have been made to deliberately manipulate percept quality [22, 26-28], although quantitative perceptual data remain sparse.

Non-intensive perceptual attributes are known to affect perception of electrotactile intensity. Stimulus frequency or pulse rate affects a perceived stimulus quality described as “pitch” [29-31] as well as sensory adaptation [32] and pattern perception performance on multi-electrode arrays [4, 28]. Changes in electrotactile perceived intensity are easier to perceive when the stimulus waveform timing is constant [23]. Spatial pattern identification accuracy is better with waveforms subjectively rated as more localized than broad [4, 28]; objective waveform factors, specifically higher burst frequency, increased number of pulses per burst, and lower pulse repetition rates led leads to more accurate pattern identification.

The dimensions of mechanical touch have been more carefully studied, although the conceptual framework for these still lag parallel knowledge in vision and audition. One early attempt to define tactual dimensions is Titchener’s proposed “touch pyramid”, which placed various touch qualities (pressure, tickle, ache) on the vertices and edges of a square-bottomed pyramid [33 (p. 452)]. Another early researcher, David Katz, was less concerned with dimensionality *per se* than with its structure, separating characteristics that identify specific materials (*spezifikationen*) from more general surface properties such as roughness or hardness (*modifikationen*) [34]. Katz also observed the differences between gross shape and surface properties, and the intrinsically interactive and immersive nature of touch perception, a theme picked up by later researchers [35-38].

[1]http://www.wicab.com ; http://www.eyeplus2.com; http://www.heliusmedical.com

This holistic exploration of touch is complemented by the elemental approach taken by Picard [39] and Hollins [40], who attempted to characterize the perceptual space generated by fingertip scanning of textured surfaces. In each case, using multi-dimensional scaling (MDS) techniques they were able to generate classes of subjective descriptors relating to the perceptual attributes of each surface, and then associate those descriptors to 3–4 underlying perceptual dimensions. We adapted this approach to our investigation of stationary electrotactile stimuli, realizing that eliminating active object and surface exploration deprives the participant of kinesthetic information, possibly reducing overall dimensionality.

Although we did not necessarily expect to see a 1:1 correspondence of stimulus to response variables, extant results suggested that at least two perceptual dimensions would emerge and that these would correlate strongly with stimulus current and frequency. For example, to keep the perceived intensity of an electrotactile sensation constant, the stimulation level (expressed as current or pulse width) needs to decrease as frequency increases [41]. Furthermore, using a completely different methodology than our study, Van Doren [30] established contours of equal perceived frequency ("pitch") and perceived intensity ("loudness") across a range of stimulus values similar to those we studied. That study used the method of response invariance, in which participants received pairs of electrotactile stimuli on the upper arm and sequentially adjusted the current of the second (match) stimulus in each pair to match the loudness of the first (reference) stimulus. Plotting match current against match frequency (nine levels) yields an iso-loudness curve for each of the four reference current levels. Iso-pitch contours were similarly constructed by presenting the reference stimuli at three frequencies and having participants adjust the frequency of the match stimulus so that it felt like it had the same pitch as the reference. The match frequency was then plotted against ten match currents. The resulting iso-loudness and iso-pitch contours in Van Doren’s paper are reproduced below as Fig. 1. The essential results are (1) perceived loudness and pitch were strongly correlated to stimulus current and frequency, and (2) perceived intensity mildly increased with an increase in stimulus frequency, but perceived frequency was minimally affected by stimulus amplitude.

Given that psychophysical results frequently depend on particular experimental methodology, we were interested to see if using dissimilarity ratings using fixed paired stimuli rather than participant-adjusted match stimuli would yield the same strong correlation between stimulus and response as Van Doren’s results, which used response invariance[2]. Although we expected to see at least two perceptual dimensions emerge, neither our measurement method nor the MDS analysis assume anything *a priori* about percept dimensionality, and it was therefore possible that additional dimensions might emerge, given the wide range of electrotactile sensations that have been reported [4, 22, 23, 27, 42-45].

[2]One might argue that Van Doren’s study also employed paired comparisons because it is based on a Békésy tracking method, in which participants discriminated whether the match stimuli were stronger/weaker or higher/lower pitch than the reference, and that this information was used to adjust the match stimulus current or frequency, respectively. There are, however, two crucial differences. First, Van Doren’s study forced participants to attend *specifically* to perceived intensity or perceived frequency, whereas our participants were given no such constraint, and instead were encouraged to only rate the “dissimilarity” of the stimuli in each pair, regardless of the nature of the individual stimuli. Second, the paired judgments that participants made in Van Doren’s study were only incidental to their primary task, which was to achieve response invariance (or similarity). In our case, we directly measured the response *dissimilarity*.

METHODS

A. Participants

Fifteen healthy adults (11 M, 4 F; mean age: 25.6 yrs, SD: 6 yrs) participated in this experiment after providing informed consent under a protocol approved by the University of Wisconsin-Madison Health Sciences IRB. While none had prior experience with electrotactile stimulation, all first underwent preliminary screening to estimate their stimulus dynamic range (SDR) using a waveform and electrode identical to that in the present experiment (10 and 100 Hz), using the middle finger of their non-dominant hand. SDR is defined as IM /IS, the current at maximal level without discomfort, and the sensation threshold, respectively, using a method of adjustment [43]. The fifteen participants exhibited consistent performance (less than 20% variation in IS and IM across 5 trials) and had SDRs (1.33 – 7.42) that were considered adequate to ensure that the multiple levels tested were not too close together. One participant's dataset was later discarded because it had inadvertently become corrupted, so the results show data from only fourteen participants.

B. Electrotactile System

After the participant washed his or her hands, the electrode array surface and middle finger of the participant's non-dominant hand were then cleaned with 71% isopropyl alcohol. Participants had a single coaxial electrode fixed on the distal pad of the finger using a modified aluminum sport splint (Fig. 2). The electrode had an active center 0.8 mm diam. and an annular return ring 4.0 mm inner diam., 6.0 mm outer diam. with an air gap insulator between the active and return elements. Once the electrode was mounted on the participants' finger it was not disturbed for the remainder of the experimental session. This was done to minimize differences in localized skin hydration and therefore impedance, variations of which could potentially alter the current necessary to achieve supra-threshold stimulation [46-48].

Capacitively-coupled (zero dc), rectangular, positive, 50-μs-wide current-controlled pulses (0–18.2 mA) were delivered to the center element of the electrode. Electrotactile waveforms were generated by a programmable Tucker-Davis[3] RP2.1 digital signal processor and custom software running on a personal computer. The voltage output from the RP2.1 was converted to a current-controlled pulse waveform by a custom transconductance amplifier having a nominal gain of 2 mA/V, a maximal current capability of 20 mA, a maximal compliance of 510 V, and an output resistance of 8.8 MΩ [49].

C. Experimental Design

In a full-factorial design, we manipulated two variables, current, *I*, and frequency, *F*, at four levels each. The four frequency levels were 10, 15, 35, & 100 Hz (pulses/s); 10 and 100 Hz constitute the ends of the useful sensation range for this simple waveform. Lower frequencies tend to feel pulsatile; higher, like pressure [22, 44, 45]. The two intermediate values, 15 and 35 Hz, identified from the results of an unpublished preliminary study, were

[3]http://www.tdt.com/

selected to achieve approximately uniform perceptual frequency increments as a function of the changes in the stimulus frequency.

Similarly, the participant-dependent current levels, I_S (the sensation threshold), and I_M (the maximum current without discomfort) were used to determine the four current levels used in the experiment. Values for I_1, I_2, I_3, and I_4, were selected to achieve approximately uniform differences in the perceived change of sensation intensity, ΔΨ, as a function of the stimulus current, I, and were constrained by the following relationship IS < $I_1 < I_2 < I_3 < I_4 < I_M$. (See Appendix for details.)

The four current levels and four frequency levels yield a total of 16 conditions: $C_1, \ldots C_{16}$. In each session, the participant was presented with all possible dissimilar condition-pairs, or $16^2 - 16 = 240$ pairs (i.e., excluding the principal diagonal). The order of the stimulus pairs could be presented in one of two possible formats, i.e., given that $x < y$, the stimulus pairs could be presented as C_x, C_y (format 1), or C_y, C_x (format 2), completing the upper-right or lower-left halves of the full-factorial matrix, respectively, and separated by the principal diagonal. For each participant, the format in the first phase was determined randomly and the next phase was simply the alternate format. For the same participant in the second session, the order of the formats was reversed. This counter-balancing scheme was maintained across all participants. We did not present the entire matrix at once because the resulting continuous session would have been fatiguing for the participant.

D. Procedure

Each participant completed two sessions, and each session comprised three phases. At the beginning of each session (phase zero), the participant's I_S and I_M values were computed from the average of five successive measurements at each condition using a method of adjustment technique (with random offset assigned to the knob position to prevent participants from relying on proprioception while making their estimates). The four current levels, I_1, I_2, I_3 and, I_4, were calculated from I_S and I_M (see Appendix). In phase one, the participant was presented with 120 condition-pairs from the 16 conditions in one of the two formats. For each condition-pair the participant judged the dissimilarity between the first and second condition in that pair. In phase two, the participant performed the same task as in phase one but with the opposite format. A typical session lasted approximately 90 minutes. In the second session, typically scheduled 24-72 hours after the first one, participants followed the same procedure as above except that the format order was reversed to counterbalance the design and eliminate possible order effects.

Each trial consisted of a 1-second stimulation using the first condition, C_x, of the pair, a 1-second inter-stimulus interval, and then a 1-second stimulus for the second condition, C_y, of the pair. The onset of each trial was preceded by a unique tone presented 0.5 s before the onset of each stimulus. Participants responded by adjusting the position of a cursor on a continuum line displayed on an LCD video monitor by manipulating a computer-gaming joystick. The endpoints of the scale were labeled "Same" and "Different" and this range was linearly coded to a number between zero and one. The participant's task was to provide an estimate of the relative 'difference' in the sensation quality of the paired stimuli. The joystick had a random position offset to prevent habituation and forcing the participant to pay attention to the cursor position, not the joystick, to respond to each trial.

RESULTS

MDS analysis uses a matrix of proximity measures that quantify the degree to which any two objects are alike [50]. In this study, the values of the matrix are dissimilarity values, i.e., the proximity measure is an indication of "difference". We used MATLAB (version 7.2) to implement a non-metric MDS analysis using Euclidean distance measures. A non-metric analysis respects the ordinal characteristics of the underlying dissimilarity scale. The goodness-of-fit criterion selected for minimization was Kruskals' [50] normalized stress formula one (stress-1) [51].

For each phase, the dissimilarity ratings were used to create a 16-by-16 dissimilarity matrix: M represents a generic matrix, while $M^{(i,j,k)}$ denotes the dissimilarity matrix obtained in the k^{th} phase of the j^{th} session, for the i^{th} participant. For each participant, the dissimilarity judgments for the two sessions, each with two formats, are plotted as: $s_j m_k$, where j, k ={1,2}.

For each dissimilarity matrix, two graphs were obtained — the scree plot and the final configuration plot. The scree plot is an x-y scatter plot of stress values (an index of model lack-of-fit, on the y-axis) versus number of dimensions (on the x-axis). From the scree plot, the dimension that *best* fits the data is determined and the corresponding final configuration of the objects is plotted in that dimension.

The scree plots shown in Figure 3(a) are those for a single representative participant (identifier i=27). It shows the results based on the dissimilarity matrices from each of the four phases for the participant and labeled, (s_1m_1, s_1m_2, , s_2m_1, and s_2m_2). The figure also shows the scree plot (labeled "*sm*") based on the average of the dissimilarity matrices obtained for each of the four phases (2 sessions × 2 formats). More accurately, the scree plot labeled s_jm_k was obtained from the dissimilarity matrix, $M = M^{(27,\mathrm{j,k})}$, and "sm" was obtained from the dissimilarity matrix, $M = \frac{1}{J \cdot K} \sum_{j=1}^{J} \sum_{k=1}^{K} M^{(27,j,k)}$, where J = 2 and K = 2 (two sessions and two phases), that is, the mean of the four dissimilarity matrices, s_jm_k, described above, for participant number "27". Note that stress for the mean matrix is lower than the mean of the stress for each phase matrix because calculating stress in MDS is not a linear transformation; averaging the four phase matrices lowers the overall "measurement noise" which is reflected in the lower stress value across higher dimensions.

Scree plots for each of the 14 participants are shown in Figure 3(b). For each participant, i, the scree plot was obtained from the mean dissimilarity matrix. While there is inter-participant variation, the trend of decreasing stress with increasing number of dimensions is consistent across all participants.

The overall participant response for all trials in format 1 versus format 2, that is, the presentation order of each stimulus pair, was compared using analysis of variance

(ANOVA). Order was not statistically significant (p=0.49). Similarly there was no difference between phases 1 and 2 (p=0.58), suggesting no effects of training or fatigue on overall performance.

The scree plots for the four dissimilarity data sets (two sessions, with two phases each), were averaged across all participants to obtain the dissimilarity matrix, $M = \frac{1}{N}\sum_{i=1}^{N} M^{(i,j,k)}$, N = number of participants, and are shown in the four traces labeled $s_j m_k$ in Figure 3(c). The plots all have similar shapes, visually affirming that there was no significant effect of stimulus pair order (format) or practice/fatigue (phase) on overall performance. Finally, the 14 composite matrices from all participants were averaged to generate a final dissimilarity matrix, $M = \frac{1}{N \cdot J \cdot K}\sum_{i=1}^{N}\sum_{j=1}^{J}\sum_{k=1}^{K} M^{(i,j,k)}$, where participants, N = 14, sessions, J = 2, and phases, K = 2. This is shown as "*sm*" in Figure 3(c).

In determining the number of dimensions that best fits the data, the number of dimensions at the "elbow" of the scree plot is typically chosen. This can be viewed as the minimum dimension after which the plot starts to level off, so that while additional dimensions further reduce the stress value (especially if stress is < 0.1), their contribution to the stress reduction is marginal [50, 51].

The 2D final configuration plot shown in Figure 4 depicts the relationship between the two stimulus variables and the two perceptual dimensions suggested by the scree plot "*sm*" in Figure 3(c). Figure 4 is actually a scatter plot of the mean relative distances of all 16 conditions for all participant and trials, the connecting lines representing interpolated iso-current and iso-frequency contours in stimulus space. A 16-degree clockwise rotation was applied to the plot to align one of the perceptual axes to a Cartesian coordinate system to make interpretation easier. This can be done without any loss of fit to the data because Kruskal's stress formula-1 is a Euclidean model [50, 51].

DISCUSSION

The scree plots in Figure 3(c) strongly suggest that the majority of the participant response can be represented by two dimensions in percept space. This trend is evident in all of the curves, and most obvious in the "*sm*"curve. At two dimensions an elbow is observable, wherein the stress value drops sharply to less than 5%, which indicates that the perceptual space corresponding to the given stimulus space (dissimilarity matrix) can be adequately represented in two dimensions. Furthermore, based on the monotonicity of the iso-current and iso-frequency contours in Fig. 4, we may reasonably associate perceptual frequency (MDS Dimension 1) with stimulus frequency, and perceptual intensity (MDS Dimension 2) with stimulus current. It appears that participants relied most heavily upon these two qualities or attributes to make their dissimilarity estimates. This conclusion appears consistent with a common-sense example. If, when comparing two of the stimuli, participants both noticed that one was much stronger in intensity and also had a much more of a pulsatile characteristic, then they would likely provide large dissimilarity ratings; this is observed in points A and P in Fig 4. A similar, converse, argument could be made for points D and M, which likewise result from maximal differences in both stimulus frequency and current. The difference between the A–P and D–M distances further suggests that the two perceptual dimensions are not associated 1:1 with the corresponding stimulus dimensions; this apparent interaction is discussed next.

A. Effect of Current on Perception of Frequency

The greater distance between points M and P in Fig. 4 (high current, 100 and 10 Hz) relative to points A and D (low current, 100 and 10 Hz) indicates that *higher stimulus currents result in a greater range of perceived frequency*. In practical terms, this means that coding information by frequency may work best at stimulus levels that are well above sensory threshold. This result is similar to that observed in color vision, where color perception is relatively poor at very low light levels (scotopic or night vision) as compared with brighter illumination levels (photopic or color vision) [16], and in audition, where pitch discrimination is better at higher sound pressure levels [52].

This finding is not unexpected given the expected recruitment pattern of cutaneous afferent fibers for electrotactile stimulation. As current increases, the response of an individual afferent fiber increases quickly from no activity, to sporadic and demultiplied firing (< 1 action potential, AP, for each stimulus pulse), to entrained firing (one AP per stimulus pulse). Because only a 5% increase in current is necessary to progress from sporadic firing to entrainment [25], we postulate that the perceived electrotactile intensity is mediated more by fiber recruitment than by individual fiber activity. As a consequence, much more information is available to the brain (in the form of synchronized somatosensory afferent activity) as current increases, presumably enhancing frequency discrimination capability.

Anecdotally, we have observed that low-perceived-intensity (near sensation threshold) electrotactile sensations feel similar regardless of waveform timing, and that frequency changes are difficult to perceive. Van Doren [30] made a similar observation, and careful examination of his iso-perceived-frequency (iso-pitch) contours (reproduced in Fig. 1) reveals a similar compression of perceived frequency at low stimulus currents. We therefore conclude that even with very different methodologies (paired-comparison dissimilarity ratings in our study versus participant-initiated pitch matching in Van Doren's), stimulus frequency perception is enhanced at higher stimulus levels.

The difficulty in discriminating frequency changes at very low perceived intensities suggests that the perceptual space would collapse to a small area near sensory threshold. The diagram in Figure 4 illustrates this concept by extrapolating the iso-frequency lines to lower stimulation levels than those used in this experiment[4]. Although there is some error in the convergence, we hypothesize that in percept space there is a single point corresponding approximately to sensory threshold. A future experiment exploring very low stimulus levels is necessary to test this hypothesis.

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[4]The MDS analysis we used is non-metric, meaning that only monotonicity, not relative distance, is guaranteed in the calculated dimensions. However, the linearity of the iso-frequency contours suggests that relative distance *is* preserved, justifying our extrapolation.

B. Effect of Frequency on Perception of Current

A second and related observation indicating interaction of the stimulus variables is that *higher stimulus frequency results in a greater effect of stimulus current on the perceived sensation*. For example, the distance between point A and M (100 Hz, low and high currents) in Fig. 4 is greater than the distance between D and P (10 Hz, low and high currents). This effect is also observable in the iso-perceived-intensity (iso-loudness) contours noted by Van Doren, but is much smaller than the effect of current on perceived frequency described above. This smaller effect makes intuitive sense in that the perceived intensity of a tactile stimulus is relatively easy to discriminate even at very low stimulus frequencies (for example, 1 Hz, or wristwatch second-hand rate tactile taps). It is also consistent with the neurophysiological response, where we presume that for any current yielding a sensation, the number of cutaneous afferent fibers recruited is determined more by current than by frequency, and therefore the effect of frequency on perceived current is presumed small. Limited preliminary (unpublished) data similar to those reported in [25] showed easy entrainment of mechanoceptive afferents to electrotactile pulses up to 50–100 Hz.

C. Compression of Response to Frequency

The reported dissimilarity (i.e., the space between the dotted lines in Fig. 4) as a function of stimulus frequency appears neither linear nor logarithmic. While the latter relationship might be expected as a consequence of Weber’s Law, the sensation of 35-Hz stimuli appears more similar to that for 100 Hz (a frequency ratio of 2.9) than that for 15 Hz (frequency ratio 2.3). This finding, however, is consistent with previous reports that the just-noticeable-difference for electrotactile frequency in the 15–35-Hz range is smaller than that for the 35–100-Hz range (i.e., that the perceptual response to frequency in the low range is stronger), and that electrotactile frequency perception generally decreases above 100 Hz [24].

D. Application to Tactile Information Display

Insights into the perceptual response to these two stimulus variables have both practical and theoretical interest, particularly in light of results congruent across laboratories, methods, and skin type and locus (glabrous fingertip in this study and hairy upper arm for Van Doren’s study). For example, these results may aid development of tactile graphic displays for low-vision or blind computer users [4]. Such a system could code both intensity and frequency to reliably present graphic information. The further ability (via even more sophisticated waveform manipulation) to predictably encode qualities of sensation to convey specific meaning: e.g. analog hue and saturation in color vision, pitch & loudness of sound, or texture and hardness in tactile exploration of a surface, contact force and surface compliance or coefficient of friction, represents a significant development opportunity. Similar opportunities exist in the realm of virtual environments, for example for surgical robotics and training [53].

These results also encourage exploration of other variables such as pulse rate within bursts, and burst structure, both of which can be modulated to affect not only perceived tactile intensity but also the qualitative nature of the percept, e.g. eliciting the sensation of vibration vs. tingle vs. pressure, or what Aiello [23] and Kajimoto [27] called "tactile colors". (In fact, there is not yet an adequate nomenclature for describing the types of sensations elicited by electrotactile stimulation).

The processes underlying these observations are also of theoretical interest in that we seek to understand and characterize the relationship between physical and percept space. Our unpublished pilot experiments suggest that even greater dimensionality may be possible. For example, while the present study used a steady stream of current pulses, there is strong evidence that breaking up this steady stream into bursts has desirable effects on the comfortability of the electrotactile percept [22, 54]. These, and other unpublished studies in our lab, suggest that a nested burst structure (i.e. bursts containing sub-bursts) may allow manipulation of up to five burst structure and timing variables. How this capability is utilized may depend on future research exploring perceptual differences between individual users as well as the overall system configuration (i.e. electrode arrangement, information coding scheme, etc.).

With a more sophisticated understanding of how to modulate the stimulus structure and control the behavior of the human-machine interface we envision that a control system can be developed to allow predictable and reliable presentation of specific sensations for information communication through the haptic channel.

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APPENDIX

To determine the experimental current levels, two participant-dependent variables were measured (for each participant and session): I_S (sensation threshold) and I_M (maximum current without discomfort). Each participant performed five sequential estimations of each level and the mean values for I_S and I_M were calculated. The four experimental levels were then determined by establishing approximately uniform differences in perceived intensity, $\Delta\Psi_I$, and then calculating the values of I using Stevens' Power law, $\Psi_I = (I-I_s)^n$, assuming n=2 [18, 20, 21]. For each participant and session we set I_1 at a low supra-threshold level, I_4 at a strong sub-maximal level, with I_2, and I_3 in between. The relevant algorithms are:

$$I_1=I_s+0.3(I_M-I_S) \qquad I_2=I_S+\sqrt{\frac{1}{3}\left[(I_4-I_S)^2+2(I_1-I_S)^2\right]}$$

$$I_3=I_S+\sqrt{\frac{1}{3}\left[2(I_4-I_S)^2+(I_1-I_S)^2\right]} \qquad I_4=I_S+0.9(I_M-I_S)$$

Note that while our methodology attempted to achieve approximately-equal changes in the electrotactile percept in response to increments in stimulus current and frequency, neither the experimental paradigm nor the MDS analysis *require* this. No loss of generality results from any lack of equal increments in stimulus or perceptual space.

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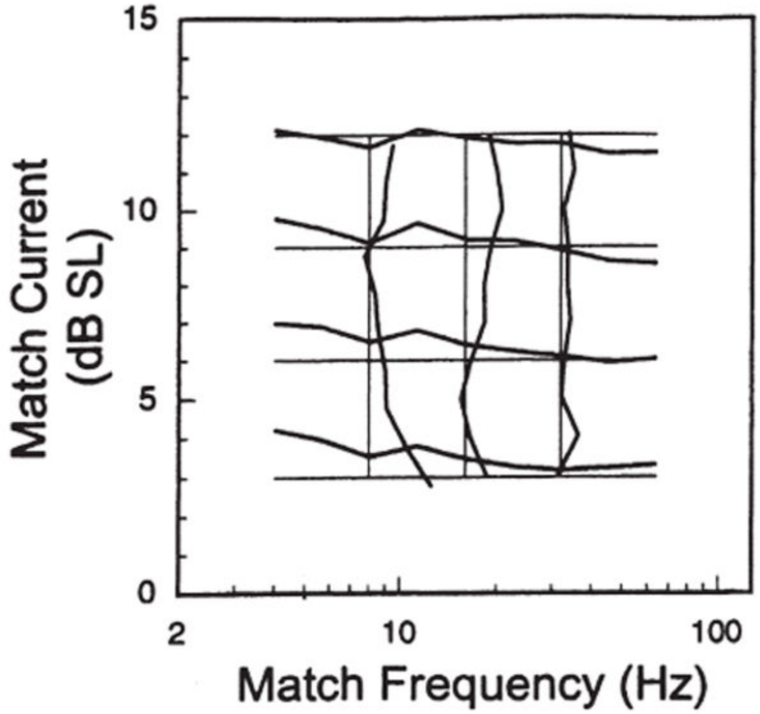

Figure 1.

Figure 6.A from Van Doren [30], used with permission. Thick lines are the measured response equal-sensation contours. Thin lines are idealized orthogonal contours. These are averaged results (over all participants) from an experiment using a stimulus (amplitude or frequency) matching 2AFC paradigm. Contours of equal perceived amplitude were measured at four amplitudes (3, 6, 9 , and 12 dB) relative to the threshold of the 16 Hz reference stimulus, using one sweep direction in each of the 4 experimental sessions. Contours of equal perceived frequency were measured at three reference frequencies (8, 16, and 32 Hz) as the match amplitude was swept in 1 dB steps from 3 to 12 dB (relative to the sensation threshold at 16 dB) or the reverse.

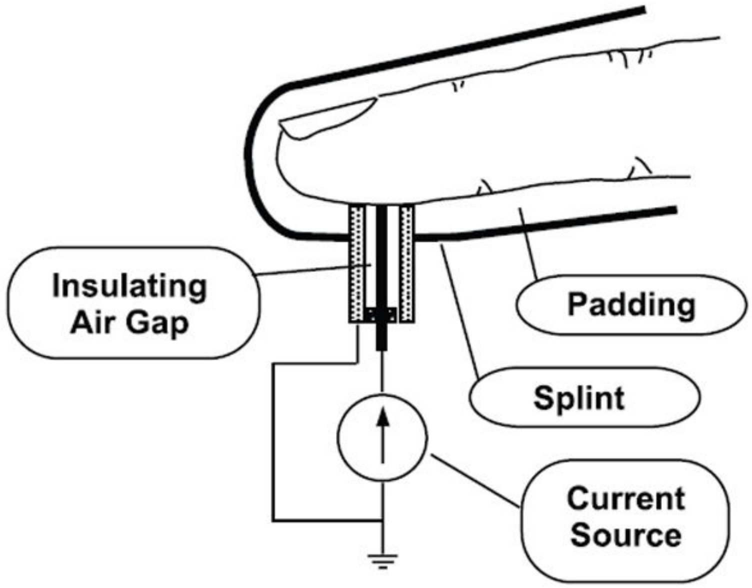

Figure 2.
Electrotactile stimulation system. A constant-current source delivered electrotactile pulses to the fingertip via a coaxial electrode affixed to the finger using a modified sport splint (see main text).

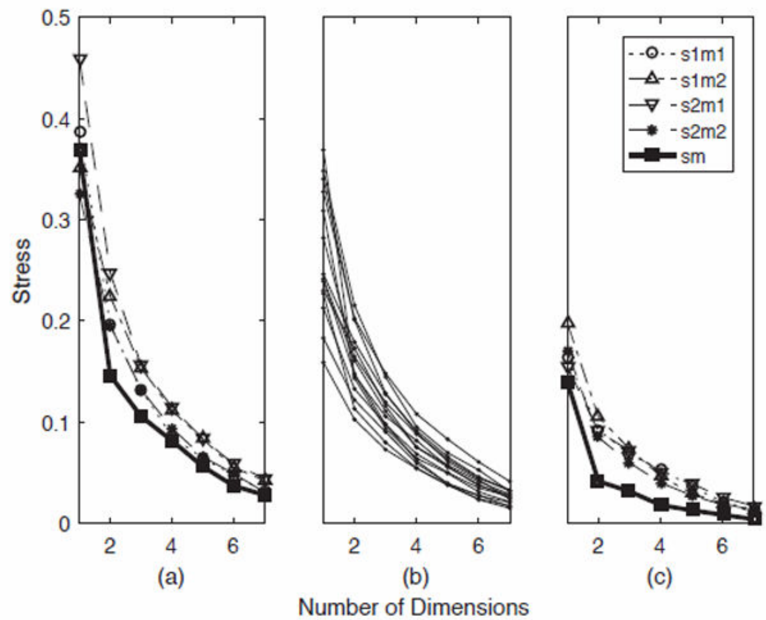

Figure 3.

Scree plots, representing lack of model fit (see main text) for the dissimilarity estimation task. (a) Single representative participant. Each trace "sjmk" represents the mean response for each format, while trace "*sm*" is the average overall response for this participant. (b) Mean response, "*sm*", for each of the 14 participants. (c) Mean dissimilarity responses for each session and format, averaged across all participants (labeled *sjmk*), and mean overall response across all participants, sessions, and phases (labeled *sm*).

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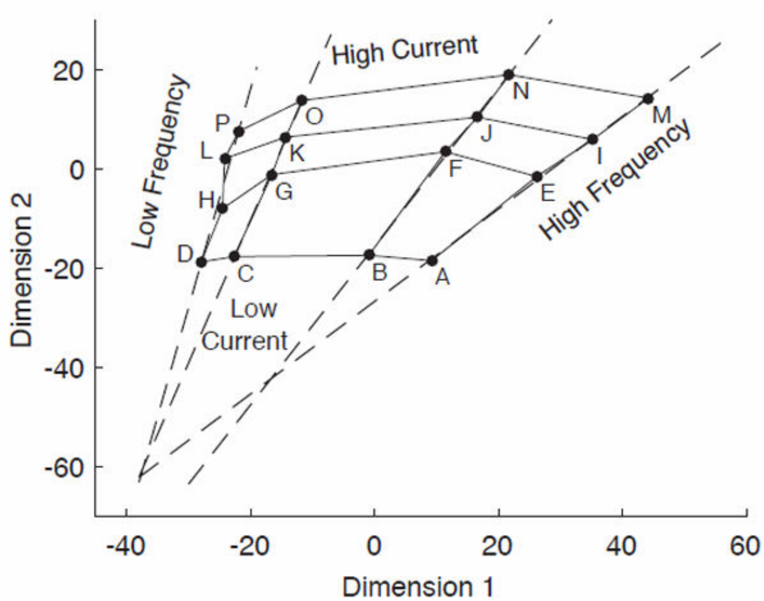

Figure 4.

Overall Configuration Diagram depicting the relationship between physical variables and the perceptual space dimensions, derived from the mean of the dissimilarity responses for all participants, sessions, and phases. Connecting lines are a visual aid. Dashed lines extrapolate the iso-frequency contours (10, 15, 35, 100 Hz), showing a trend toward decreasing frequency perception as intensity decreases.