

Short Papers

Establishing Natural Tactile Mappings: Mapping Tactile Parameters to Continuous Data Concepts

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Abstract—There has been limited work developing natural mappings between tactile signals and common data concepts in data rich domains. If these mappings can be established, tactile displays can become more intuitive and readily adopted. The present study aims to identify general natural mappings between perceptual dimensions of vibration and continuous data concepts. Twenty-one participants were tasked to map four different tactile parameters to four different data concepts—pressure, concentration, size, and speed. We found that an increase in intensity was good at conveying increases for all data concepts. We also found that speed, pressure, concentration, and size all have at least one strong natural mapping.

Index Terms—Natural mapping, applied domains, user-centered design.

I. INTRODUCTION

The tactile channel is a promising means to display information to humans and reduce demand on visual and auditory attentional resources [1]. The visual and auditory channels can easily carry information about events, numbers, objects, and even abstract ideas using natural language and symbolic cues. However, tactile cues are limited given they convey information with less straightforward structures of meaning. To address this, researchers have explored different ways of improving information transfer in tactile displays, such as creating haptic icons [2], [3], haptic metaphors [4], [5], [6], and even haptic language [7].

Well-designed tactile displays can improve the bandwidth and richness of informational displays for human operators in a variety of contexts and settings. For example, haptic icons have been shown to effectively communicate upcoming events and how soon they will occur [2]. Tactile stimuli can also help drivers maintain their speed better than traditional speedometers alone [5]. In a data-rich environment, discrete and continuous tactile displays can improve patient monitoring performance by anesthesiologists [4]. However, tactile parameter use varies widely from study to study, showing that there is no consensus on the most effective way to encode tactile information.

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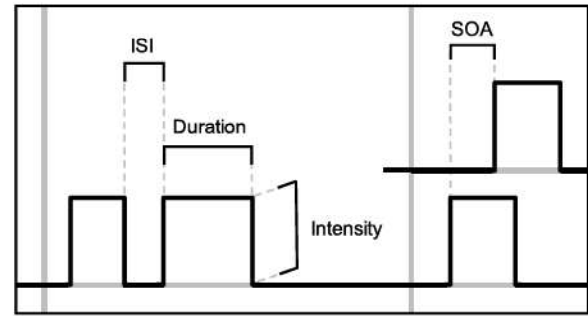


Fig. 1. Visualizations of inter-stimulus interval (ISI), pulse duration, intensity, and SOA for hypothetical tactile stimuli. Intensity is plotted on the vertical axis and time is plotted on the horizontal axis. For SOA, two stacked line charts indicate the activation of two different factors.

To address this limitation, the present study aims to explore general natural mappings between four perceptual dimensions of vibrations and four continuous data concepts. This work provides a starting point for creating intuitive tactile mappings that can be used to display information in a variety of data-rich domains.

A. Tactile Parameters

Many parameters can be used to change the way tactile pulses feel. The parameters of the signal itself include roughness (e.g., square, sinusoid, or modulated wave), frequency (wave rate), intensity (amplitude or surface acceleration), and duration (on time of a pulse). When using multiple pulses, the parameter of inter-stimulus interval (ISI) controls the off time between pulses. When using multiple tactile actuators (tactors), many other possibilities arise, such as tracing paths or symbols on rows and grids of tactors [8].

For the purposes of this study, four parameters were chosen as a Fig. 1 starting point. Roughness and frequency, specifically, were excluded in this initial investigation because: (a) prior work suggested they might have perceptual overlap with intensity [9], [10], (b) appropriate frequency ranges might not be practical for real world applications [9], [11], and (c) the experimental setup was best suited to a constant, unmodulated frequency [12]. Additionally, spatial parameters (e.g., the number of tactors activated sequentially) were excluded to narrow the scope of the study. The parameters used here include: (1) intensity, (2) pulse duration, (3) inter-stimulus interval, and (4) stimulus onset asynchrony of apparent tactile motion which will now be described in turn.

- **Intensity:** Intensity describes how strong a tactile pulse feels. This can be affected by the signal amplitude, frequency, and

waveform [6], [9], [12], [13]. For this study, intensity was varied by modulating the amplitude only. Naturally, intensity is used in tactile displays to communicate magnitude, strength, or severity [4].

- *Inter-Stimulus Interval (ISI)*: The off time between pulses, is also inherent to any tactile rhythm. Like musical rhythms, tactile rhythms are made up of pulses of different lengths, separated by spaces of different lengths (ISI) [2], [8]. Changes in ISI can be noticed discretely and associated with different ideas. ISI can also be used continuously to change the speed of a presentation of several pulses.
- *Duration*: Duration is the amount of time a tactile stimulus is active. Like ISI, pulse duration can be noticed discretely or continuously. Longer durations can also be used to give someone more time to feel a stimulus, but this does not necessarily mean people will perceive more information from the stimulus [8].
- *Stimulus Onset Asynchrony of Apparent Motion*: When multiple tactors are distributed on the body, the location of a pulse can convey meaning discretely. Similarly, patterns can be traced to convey discrete information. One commonly used parameter is stimulus onset asynchrony (SOA), which mediates the time between the start of pulses on different tactors [8], [14], [15]. If pulses do not overlap, ISI can be used instead of SOA [8].

B. Data Concepts

For the purposes of this study, four different data concepts were used to identify potential natural tactile mappings. While not exhaustive, these provide a useful starting point for understanding how common scales in data-rich domains can be mapped into the tactile modality. These concepts were identified with the hope that most data scales in the physical world could align with at least one concept.

- *Pressure*: Pressure data conveys forcefulness or compactness. For example, while tele-operating an excavator, an operator might encounter varying levels of resistance from different types of soil [16]. Also, this is useful in a healthcare setting when providers need to monitor a patient's blood pressure that may increase or decrease [4], [17].
- *Concentration*: Concentration data conveys a proportion or ratio of a whole. For example, a pilot might need to know their plane's angle of attack [18] or a bus driver might need to monitor the number of passengers relative to the capacity.
- *Size*: Size conveys how large or numerous something is, irrespective of capacity. For example, the size of a crowd might be monitored by security service at a large outdoor event [19]. In another situation, a networking specialist might monitor the number or size of outgoing TCP packets.
- *Speed*: Speed conveys how fast something moves or happens. For example, a driver monitors the speed of a vehicle [5] or a shipping yard manager may measure the container loading rate onto carriers.

C. Objectives

Existing techniques take a discrete approach to displaying information through the tactile modality [2], [6] or bucket continuous parameters into levels according to heuristics [16]. There is a gap in the literature regarding mapping tactile parameters onto continuous data concepts. Specifically, there is a lack of empirical evidence about how humans prefer to map tactile parameters to data concepts when no strategies or rules are prescribed. The present study aims to address this gap by determining whether there exist natural mappings between



Fig. 2. Experimental setup and hardware used (From top left clockwise: headphones, monitor, keyboard, mouse, armband with tactors, C-2 tactor box).

four tactile parameters and four data concepts. This can provide a basis of study for building intuitive tactile displays for continuous data.

It was expected that higher intensity would correspond to higher conceptual magnitudes for all four concepts. Longer ISI, pulse duration, and SOA, which increase the total cue presentation time, were predicted to correspond to slower apparent speeds. Due to divergent strategies in pilot testing, apparent speed was also predicted to have both an increasing and a decreasing group for pulse duration.

II. METHODS

A. Participants

Twenty-one students and staff at University of Virginia participated in the experiment (9 female, 10 male, 2 non-binary; mean age 22.9 = years, SD = 4.9). The participants consisted of 10 undergraduate students, 8 graduate students, and 1 staff member. Participants were compensated \$15 per hour of their time in digital gift card credit.

B. Experimental Setup

Fig. 2 shows the experimental setup that included a 19" (4:3 aspect ratio) Dell computer monitor that displayed the user interface, a standard mouse and keyboard, Bose Quiet Comfort 15 noise cancelling headphones, control box to transmit the tactile cues, and a custom elastic armband outfitted with three C-2 tactors (Engineering Acoustics, Inc., Casselberry, FL) to present vibrotactile cues. These solenoid-based actuators measure 3.05 cm in diameter and 0.79 cm in height with a maximum 1 mm displacement. Participants wore the band on the upper left arm with tactors facing outward to the left. This positioning has been used in past studies with similar hardware due to high detection accuracy on the upper arm and minimal interference with movement and use of the hands [17], [20].

C. Task

Participants were tasked to assign values of the tactile cues presented to the four concepts (e.g., concentration). For each trial, participants pressed the play button to start "clips" of vibrotactile cues (Fig. 3). The cues used were in the form of pulses, produced by activating a tactor to a set amplitude and frequency, delaying for some duration, and then deactivating the tactor. Then participants would assign a numerical value to the clip with respect to a particular concept. For example, with the interface shown in Fig. 3, the concept was size. For instance, if a



Fig. 3. Interface on the first practice trial.

TABLE I
INDEPENDENT VARIABLE LEVELS

Level	Intensity	ISI	SOA	Duration
L1	51	100	225	150
L2	102	300	325	325
Baseline	153	500	425	500
L3	204	800	550	800
L4	255	1100	675	1100

participant assigned the value 13 to Trial 1 and the value of 26 for Trial 2, this would indicate that they believed that the Trial 2 clip was twice as great in size as the baseline clip.

Each clip included eight pulses (i.e., activate, delay, deactivate). These clips were varied with respect to each of the four identified dimensions of tactile cues. Pulses for the apparent motion clips consisted of three sub-pulses, each on a different factor. Frequency was set at 250 Hz throughout the study as this is the recommended resonant frequency for the C-2 tactor [2]. Except when duration was varied, pulses were 500 ms long. Similarly, ISI was set at 500 ms unless spacing was varied. The tactors accepted a unitless intensity setting from 0–255. A standard setting of 153 units was used, which was varied only to change intensity. This value was chosen for its placement evenly between 51 units and 255 units. During pilot testing, 51 units was the lowest intensity that participants could easily feel.

The first trial of each experimental condition was always a baseline consisting of eight identical cues with standard parameter levels. All other trials contained a change in the independent variable corresponding to the current condition: amplitude gain, ISI, pulse duration, or SOA. Before the change, cues were identical to baseline cues. The change was an adjustment of the independent variable from the standard level to one of four other levels (Table I). Two levels were below the standard level, and two were above it.

D. Experimental Design

This study used a 4 (tactile parameters) $\times$ 4 (data concepts) $\times$ 4 (parameter levels) full factorial design. This resulted in four blocks (one block for each concept) with four subblocks (one subblock for each tactile parameter) of 13 trials (one baseline and 12 treatments). Each subblock of 13 trials modulated one tactile parameter and included five levels (Table I). The order of the four subblocks were randomized for each block and the order of the blocks was randomized. The baseline

for a set was always presented first, followed by a randomly ordered presentation of three trials of each parameter level (Table I).

E. Experimental Procedure

After providing an overview of the study, informed consent was obtained from the participants. The experimenter helped the participant to secure the vibrotactile armband to the upper left arm, adjusting for snug but comfortable fit. A training session helped the participant understand the interface and task. Participants were allowed to complete as many practice trials as needed. Before beginning the experimental portion of the study, participant demographic information was collected, and a comfortable level of brown noise was set on the headphones to mask the noise from the tactile cues.

For the baseline trial (Fig. 3), participants were asked to press the play button to play a baseline clip of eight identical pulses and to enter a number with the keyboard representing the magnitude of the current concept that the clip seemed to represent. They were encouraged to choose any positive number that they deemed appropriate for this baseline stimulus to establish the baseline estimate. For each of the subsequent trials, participants were again asked to play a clip of eight pulses. However, these clips contained a change in a tactile parameter. Participants were then asked to assign a number estimating the magnitude of the concept that the changed pulses seemed to represent, relative to the baseline estimate they provided. Participants were invited to take breaks as needed. Once all trials had been completed, a debriefing survey was administered, asking about which parameters participants noticed, which were natural and unnatural to map to concepts, and what mapping strategies were relevant to the tasks.

III. RESULTS

A. Quantitative Analysis

The resulting data set contained one baseline estimate and 12 treatment estimates for each of the 16 parameter-concept combinations for a total of 208 data points per participant.

Provided estimates were normalized to a ratio of the baseline estimate. A geometric mean of the ratios at each tactile parameter level was calculated, producing a single “mean ratio” for each of the four treatment levels for each parameter concept combination [21]. One participant provided zero estimates on two combinations, so their data was excluded for those combinations, as a geometric mean of such estimates would be meaningless [22].

First, a one-way repeated measures ANOVA was conducted to determine whether there were statistically significant differences in estimates over the four concept blocks. The assumption of sphericity was met, as assessed by Mauchly’s test of sphericity, $\chi^2 = 3.51$, $p = .622$. The changes in concept did not elicit statistically significant changes in estimate ratios over the course of the experiment, $F(360) = 0.679$, $p = .568$, $\eta_p^2 = .033$. That is, there is no evidence to suggest that participants’ ratings were systematically biased based on the current concept.

Next, linear regressions were performed for each of the 16 parameter-concept combinations by excluding the baseline ratio but fixing the regression line to pivot about the baseline point. This method was chosen to ensure the regression line did not imply a contradictory ratio of the baseline estimate to itself. The Python *statsmodels* library was used to perform the regression and assess goodness-of-fit, reported as r^2 values in Table II.

Individual regressions were performed for each participant’s estimates for each parameter-concept combination, without concern for

TABLE II
GOODNESS-OF-FIT (r^2) FOR ALL PARAMETER-CONCEPT COMBINATIONS

	Intensity	ISI	SOA	Duration
Speed	0.33	0.51	0.64	0.33
Pressure	0.79	0.20	0.24	0.26
Concent.	0.70	0.20	0.16	0.04
Size	0.82	0.08	0.03	0.51

Bolded are combinations with $r^2 > 0.50$.

TABLE III
GOODNESS-OF-FIT (r^2) FOR ALL PARAMETER-CONCEPT COMBINATIONS

Grade	Parameter	Concept	Dominant Mapping	% of n	r^2
A	Intensity	Pressure	+	100	0.79
A	Intensity	Concentration	+	100	0.70
A	Intensity	Size	+	100	0.82
A	ISI	Speed	-	100	0.51
A	SOA	Speed	-	100	0.64
B	Duration	Speed	-	90	0.49
B	Duration	Size	+	90	0.65
C	Intensity	Speed	+	80	0.49
C	ISI	Pressure	-	67	0.53
C	ISI	Concentration	-	76	0.47
C	SOA	Pressure	-	76	0.58
C	SOA	Concentration	-	76	0.45
C	Duration	Pressure	+	71	0.78
D	ISI	Size	+	57	0.57
D	SOA	Size	-	52	0.33
D	Duration	Concentration	+	52	0.63

goodness-of-fit. This method determined the overall trend of a participant's estimates. The resulting slopes were used to categorize each participant for each combination according to the following strategy:

- *Decreasing (-)*: Any set of estimates having a negative slope was considered "decreasing."
- *Constant (0)*: Any set of estimates where the same estimate was provided for the baseline as for all other stimulus levels was considered "constant."
- *Increasing (+)*: Any set of estimates having a positive slope was considered "increasing."

The percentage of participants falling in each category for each condition were computed. These combinations ranged in consistency and were graded (Table III) based on the percentage of all participants whose estimates indicated the specified dominant mapping direction (-, 0, or +), i.e., the mapping used by a plurality of participants. Goodness-of-fit is reported, but consistent agreement of participants on the best mapping trend was considered the most appropriate grading metric for identifying intuitive mappings.

B. Qualitative Analysis

Participants were also asked to mark which of the 16 mappings they preferred or found intuitive and explain why. They were also asked to explain their strategies. The number and percentage of participants who marked each mapping as preferred are shown in Table IV. Their written explanations were analyzed to identify any common explanations for strategies and the most preferred mappings in Table IV.

Visualization Strategies: Participants often reported using visualizations or imagination techniques to map stimuli to concepts. When they could find the concept in a real-world scenario, it was easier for them to

TABLE IV
NUMBER (#) AND PERCENTAGE (%) OF PARTICIPANTS REPORTING COMBINATIONS AS PREFERRED/INTUITIVE

Parameter	Concept	# of n	% of n
ISI	Speed	18	86%
SOA	Speed	18	86%
Intensity	Size	16	76%
Intensity	Pressure	16	76%
Duration	Size	14	67%
Duration	Pressure	12	57%
ISI	Concentration	12	57%
Intensity	Concentration	10	48%
Duration	Concentration	9	43%
SOA	Concentration	8	38%
Duration	Speed	7	33%
ISI	Size	7	33%
ISI	Pressure	5	24%
Intensity	Speed	4	19%
SOA	Size	4	19%
SOA	Pressure	4	19%

relate. Visualizations helped participants to anchor their magnitude estimates around physical phenomena, sensory experiences, or imagined activities. This was especially useful for more difficult mappings. For example, participant 15 reported that "size was a living thing walking." This helped the participant to correlate temporal characteristics of step rate to the concept of size. Participant 1 described something similar for concentration: "I thought of liquids—at first water then adding honey or syrup to increase the concentration—the more syrup/honey was added the thicker the liquid became and harder to move or stir—so that would be slower pulses and longer pulses." Even for easier mappings, visualizations helped to justify estimate strategies, as with participant 9, "with pressure, I imagined how hard I could squeeze something. With speed, I thought of conducting music."

Heuristic Strategies: Some participants preferred to abide by generalized rules and strategies. For example, participant 4 "generally followed the idea that increases in the speed/pulses/intensity mapped to higher levels of the given concept." Participant 19 "associated higher speed, longer pulses, and higher pressures with bigger magnitudes." Others developed heuristics which only applied for certain parameters or concepts, e.g., participant 18, who said, "I felt how spread out the vibrations were for speed and concentration, and I felt how intense the vibrations were for pressure and size."

Wherever possible, participants liked to group together like parameters or like concepts and treat them similarly. A tension was evident in some responses between the desire to have simple rules and the desire to handle exceptional pairings. For example, participant 6 wrote: "The larger the magnitude - the higher for all. The larger the spacing - the lower for most, depending on the concept. Speed was interpreted as more urgent which meant higher for the majority."

Intuitive Mappings: Certain comments shared by participants were specific to certain mappings, parameters, or concepts. The common sentiments for each concept are discussed as follows:

- *Speed*: Participants tended to agree that there was a very clear from movement speed across several factors to the speed concept. Regarding ISI and duration, participants often assumed a mental model without explaining it directly. ISI was more commonly mapped to speed, but pulse duration was also sometimes mapped. For example, participant 17 said, "Speed will have to do with timing between pulses." Some participants picked up on the confounding nature of these two parameters, e.g., one said, "between

this [ISI] and length, they would vary inversely, and it confused me.” Others were comfortable mapping all three.

- **Concentration:** Some participants developed strategies for concentration, but many reported struggles with it. Participant 12 shared some of their strategies: “shorter lengths of pulses and between pulses were interpreted as more packed in together, and intensity I likened to moles as in moles/liter.” Others mentioned some confusion with mapping the parameters to concentration, and issues with consistencies in their mental models. Participant 2 “I thought that a longer pulse length meant a higher concentration but was not so sure after.” For concentration, it seems that multiple mental models might be sensible.
- **Size:** Participants struggled mapping ISI, duration, and SOA to size, some noting that it was, “difficult to associate size with speed” and “confusing interpreting whether an increase in pulse space was a greater or smaller size.” Others explained rationale for why longer durations mapped to larger sizes. Rather, intensity was commonly identified as intuitively mapping to size.
- **Pressure:** Intensity was commonly mapped to pressure, followed by duration and ISI. One participant reported, “I think of pressure as the gas in a shape, so more gas means higher intensity and less space in the arm band.” Participant 15 mentioned that “longer rumbles = more pressure.” Movement speed was not as intuitive. One participant found it “difficult to correlate pressure with movement speed.”

IV. DISCUSSION

Based on the findings here we were able to establish some natural mappings for tactile parameters and generic data concepts based on the quantitative and qualitative analyses performed in this study. All participants mapped intensity to pressure, concentration, and size using positive mappings, and 80% did so for speed (Table III), confirming the first expectation and agreeing with prior work (e.g., [17]). Though, notably, only 19% of participants preferred to map intensity to speed (Table IV). Participants mostly agreed (90–100% agreement) on negative mappings from ISI, pulse duration, and SOA to speed, confirming the second expectation. As for the third expectation that pulse duration would be mapped positively to speed by some participants, this was not well supported by Table III, as only two participants (10%) disagreed with the negative mapping. However, the third expectation was supported by the fact that only 33% of participants preferred the duration-speed compared to 86% for both ISI and SOA to speed (Table IV). Mappings with A-grades in Table III show that speed, pressure, concentration, and size all have at least one mapping trend that was used by 100% of participants. Across all participants, 48% (concentration-intensity) to 86% (speed-ISI/SOA) identified these top mappings as being preferred or intuitive.

In terms of unnatural mappings, the findings show that combining temporal and magnitude is not advisable with regards to either concept-to-parameter or parameter-to-concept. As shown by the absence of any unanimous duration mappings in Table III and a maximum of 67% of participants preferring any duration mapping in Table IV, duration is somewhat difficult for people to map to concepts. This is likely because participants felt conflicted about whether to focus on magnitude mappings [23] or temporal mappings [24] for duration changes, both of which they used with 90% agreement (Table III). Concentration was the hardest concept to map, with at most 57% of participants preferring its mappings, and three C or D mappings in Table III. Finally, SOA was not ideal to map to most concepts except for speed as indicated by the C and D grades in Table III and the maximum of 38% of participants preferring non-speed mappings in Table IV. This may be due to a strong natural

association between SOA and speed that was difficult for participants to overcome.

Overall, we found intuitive continuous tactile mappings for the concepts of pressure, concentration, size, and speed. One limitation was that participants identified their preferred mappings at the end of the study, so they may have had a recency bias and difficulty remembering trials early on during the study. To mitigate this, the trials were randomized in order across participants. Future work should examine synergistic combinations of parameters to convey certain concepts. For instance, based on this work, the combination of ISI and duration may be effective in conveying speed changes. Another avenue for future work is to explore additional parameters like frequency, roughness, and spatial parameters. Also, given the open-endedness of this study, participants were not given prescribed mapping strategies. Future work can investigate the impact of prescribed strategies in helping participants learn different mappings. Finally, this was largely a laboratory-based study. There is also a need to evaluate tactile parameters in specific application contexts such as aviation [25] and healthcare [17] where there has been shown to be potential in using the tactile channel to present information.

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REFERENCES

- [1] A. E. Sklar and N. B. Sarter, “Good vibrations: Tactile feedback in support of attention allocation and human-automation coordination in event-driven domains,” *Hum. Factors J. Hum. Factors Ergonom. Soc.*, vol. 41, no. 4, pp. 543–552, Dec. 1999, doi: [10.1518/001872099779656716](https://doi.org/10.1518/001872099779656716).
- [2] L. M. Brown, S. A. Brewster, and H. C. Purchase, “Multidimensional tactions for non-visual information presentation in mobile devices,” in *Proc. 8th Conf. Hum.-Comput. Interaction Mobile Devices Serv.*, 2006, pp. 231–238, doi: [10.1145/1152215.1152265](https://doi.org/10.1145/1152215.1152265).
- [3] J. Pasquero, “Survey on communication through touch,” Central Intell. Mach., McGill Univ., Montreal, QC, Canada, Tech. Rep. TR-CIM06.04, pp. 1–28, 2006.
- [4] T. Ferris and N. Sarter, “Evaluation of multiparameter vibrotactile display designs to support physiological monitoring performance in anesthesiology,” *Proc. Hum. Factors Ergonom. Soc. Annu. Meet.*, vol. 55, no. 1, pp. 515–519, Sep. 2011, doi: [10.1177/1071181311551061](https://doi.org/10.1177/1071181311551061).
- [5] S. Yang, N. Y. You, and T. K. Ferris, “Supporting drivers in concurrent lane and speed tracking tasks with novel visual, auditory, and tactile speedometer displays,” *Proc. Hum. Factors Ergonom. Soc. Annu. Meeting*, vol. 57, no. 1, pp. 1918–1922, Sep. 2013, doi: [10.1177/1541931213571429](https://doi.org/10.1177/1541931213571429).
- [6] A. Israr, S. Zhao, K. Schwalje, R. Klatzky, and J. Lehman, “Feel effects: Enriching storytelling with haptic feedback,” *ACM Trans. Appl. Percept.*, vol. 11, no. 3, pp. 1–17, Oct. 2014, doi: [10.1145/2641570](https://doi.org/10.1145/2641570).
- [7] P. L. Brooks and B. J. Frost, “Evaluation of a tactile vocoder for word recognition,” *J. Acoust. Soc. Amer.*, vol. 74, no. 1, pp. 34–39, 1983.
- [8] S. Nataletti et al., “Temporal asynchrony but not total energy nor duration improves the judgment of numerosity in electrotactile stimulation,” *Front. Bioeng. Biotechnol.*, vol. 8, 2020, Art. no. 555.
- [9] K. MacLean and M. Enriquez, “Perceptual design of haptic icons,” in *Proc. EuroHaptics*, 2003, pp. 351–363.
- [10] H. -Y. Yao, D. Grant, and M. Cruz, “Perceived vibration strength in mobile devices: The effect of weight and frequency,” *IEEE Trans. Haptics*, vol. 3, no. 1, pp. 56–62, Jan.–Mar. 2010.
- [11] Y. Baek, R. Myung, and J. Yim, “Have you ever missed a call while moving?: The optimal vibration frequency for perception in mobile environments,” *WSEAS Trans. Commun.*, vol. 5, no. 10, pp. 1981–1985, 2006.
- [12] M. Azadi and L. A. Jones, “Evaluating vibrotactile dimensions for the design of tactions,” *IEEE Trans. Haptics*, vol. 7, no. 1, pp. 14–23, Jan.–Mar. 2014, doi: [10.1109/toh.2013.2296051](https://doi.org/10.1109/toh.2013.2296051).
- [13] B. Taylor, “Dimensional interactions in vibrotactile information processing,” *Percept. Psychophys.*, vol. 21, no. 5, pp. 477–481, Sep. 1977, doi: [10.3758/bf03199505](https://doi.org/10.3758/bf03199505).

- [14] M. Niwa, Y. Yanagida, H. Noma, K. Hosaka, and Y. Kume, "Vibrotactile apparent movement by DC motors and voice-coil tactors," in *Proc. 14th Int. Conf. Artif. Reality Telexistence*, 2004, pp. 126–131.
- [15] M. Ogrinc, I. Farkhatdinov, R. Walker, and E. Burdet, "Sensory integration of apparent motion speed and vibration magnitude," *IEEE Trans. Haptics*, vol. 11, no. 3, pp. 455–463, Jul.–Sep. 2018.
- [16] A. Smith, B. Ward-Cherrier, A. Etoundi, and M. J. Pearson, "Feeling the pressure: The influence of vibrotactile patterns on feedback perception," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2022, pp. 634–640.
- [17] K. M. Gomes, S. T. Reeves, and S. L. Riggs, "The evaluation of tactile parameters and display prototype to support physiological monitoring and multitasking for anesthesia providers in the operating room," *IEEE Trans. Haptics*, vol. 13, no. 3, pp. 628–644, Jul.–Sep. 2020, doi: [10.1109/TOH.2019.2960017](https://doi.org/10.1109/TOH.2019.2960017).
- [18] F. J. Schmidt-Skipiol and P. Hecker, "Tactile feedback and situation awareness—improving adherence to an envelope in sidestick-controlled fly-by-wire aircrafts," in *Proc. 15th AIAA Aviation Technol., Integration, Operations Conf.*, 2015, pp. 1–6, doi: [10.2514/6.2015-2905](https://doi.org/10.2514/6.2015-2905).
- [19] C. Zhang, H. Li, X. Wang, and X. Yang, "Cross-scene crowd counting via deep convolutional neural networks," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, 2015, pp. 833–841.
- [20] I. Karuei, K. E. MacLean, Z. Foley-Fisher, R. MacKenzie, S. Koch, and M. El-Zohairy, "Detecting vibrations across the body in mobile contexts," in *Proc. SIGCHI Conf. Hum. Factors Comput. Syst.*, 2011, pp. 3267–3276, doi: [10.1145/1978942.1979426](https://doi.org/10.1145/1978942.1979426).
- [21] J. C. Stevens and L. E. Marks, "Cross-modality matching functions generated by magnitude estimation," *Percept. Psychophys.*, vol. 27, no. 5, pp. 379–389, 1980.
- [22] S. S. Stevens, "On the theory of scales of measurement," *Science*, vol. 103, no. 2684, pp. 677–680, 1946.
- [23] S. Bocherreau, A. Terekhov, and V. Hayward, "Amplitude and duration interdependence in the perceived intensity of complex tactile signals," in *Haptics: Neuroscience, Devices, Modeling, and Applications*, vol. 8618, M. Auvray and C. Duriez Eds. Berlin, Germany: Springer, 2014, pp. 93–100. doi: [10.1007/978-3-662-44193-0_13](https://doi.org/10.1007/978-3-662-44193-0_13).
- [24] C. E. Sherrick and R. Rogers, "Apparent haptic movement," *Percept. Psychophys.*, vol. 1, no. 3, pp. 175–180, May 1966, doi: [10.3758/BF03210054](https://doi.org/10.3758/BF03210054).
- [25] S. L. Riggs, C. D. Wickens, N. Sarter, L. C. Thomas, M. I. Nikolic, and A. Sebok, "Multimodal information presentation in support of NexTgen operations," *Int. J. Aerosp. Psychol.*, vol. 27, no. 1/2, pp. 29–43, Apr. 2017, doi: [10.1080/10508414.2017.1365608](https://doi.org/10.1080/10508414.2017.1365608).