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Learning Vibes: Communication Bandwidth of a Single Wrist-Worn Vibrotactile Actuator

Elyse D. Z. Chase[1,2], Ali Israr[2], Pornthep Preechayasomboon[2], Sarah Sykes[2],
Aakar Gupta[2], and Jessica Hartcher-O'Brien[2]

***Abstract*— Vibrotactile feedback is increasingly common in wearable wristband devices. While much work has explored specific mappings in navigation and guidance tasks and to close the action-confirmation loop during interactions, little has focused on evaluating the communication capacity of the wrist and how it improves everyday interactions and tasks. To study these questions, we used information transfer as a metric to explore the space of signal variations within a single vibrotactile actuator (e.g., frequency, amplitude, and modulation). We ran a user study with the salient haptics cues to determine how well people were able to identify them without training on the dorsal side of the wrist, if they could interpret them better with training, and if that knowledge could be transferred to a secondary, untrained location (volar side of the wrist). Our results suggest that people are able to interpret at least 5 of the 8 cue variations, and are better able to recognize vibrotactile signals with training. We discuss the implications of the results for enabling vibrotactile interactions on the wrist.**

I. INTRODUCTION

Smart watches and other wrist-worn devices are becoming increasingly popular. These devices often use haptic feedback for simple notifications, even though recent research has shown that the wrist has capacity to convey much richer feedback about language [1], guidance [2], [3], realism [4], [5], and social touch [6]. Many actuators are able to transmit more information to the user through simple signal variations. Given a particular type of actuator, for example a voice coil motor, a single actuator has signal variations that can be leveraged for communication, such as location on the wrist as well as amplitude, frequency, modulation, and duration of the signal displayed. In this paper, we investigate how users can learn and recognize variations in signal parameters, and if particular signal variations are more salient to users when decoding tactile feedback on the wrist.

There is a significant amount of research on wrist-worn haptics, but most knowledge on the communication bandwidth of the wrist is intertwined within specific applications and methodologies. Often, exploration of this space is completed using a top-down strategy with an end application in mind, from which the mechanical design and haptics are selected. As such, many studies address each of these signal variations (e.g., frequency, amplitude, modulation), but only within a particular scope. While this is an effective strategy for testing and developing singular haptic devices, it is more difficult for others to use this information.

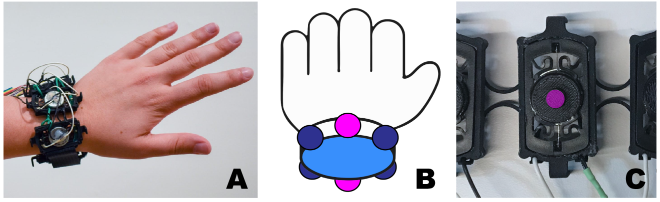

Fig. 1. (a) The haptic device attached to the left hand of the user; (b) location of actuators around the wrist, pink highlights those used here; (c) back of the actuator, pink highlights contact area with the skin.

In order to address questions surrounding the added value of haptics in user interactions, the theoretical framework of information transfer [7] helps us capture both cognitive and perceptual consequences of haptic feedback and determine its capacity, independent of specific hardware and application constraints. Such a framework could supply knowledge to designers and let them directly apply it to a new design, rather than conduct potentially expensive user testing from scratch for each new project. Moreover, the framework would provide a common ground for researchers and designers to develop and compare devices with the most intuitively interpretable haptic feedback.

In this work, we measured the vibrotactile communication bandwidth on the wrist as a function of stimulation frequency, amplitude, and modulation. In the preliminary study, we determined the information transfer when the signal was varied in one of the three signal dimensions and identified the most distinguishable features along each parametric dimension. This resulted in a set of 8 distinct and salient haptic signals to be examined further. In the main experiment, we tested eight participants in a series of blocks to determine: (i) if the 8 haptic signals were intuitive and easily recognized by users, (ii) if learning could improve recognition performance, and (iii) if learnt haptic signals could be recognized when presented at a secondary location on the wrist. We then discuss our results and conclude the paper with planned future work.

II. RELATED WORK

Haptic feedback is triggered by activating peripheral receptors in the skin, joints, and muscles, and provides users a variety of perceptual features attributed to object properties and user actions [4], [8]. On wristband consumer devices, vibrotactile stimulations are commonly applied due to high sensitivity of Pacinian corpuscles in the frequency band of 40-300 Hz [8], [9]. Typically linear resonant actuators (LRA) are packaged in the wristband to operate at a frequency in this Pacinian band (i.e. Apple Watch, Fitbit). These actuators are

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[1] Department of Mechanical Engineering, Stanford University, Stanford, CA 94305 USA `elysec@stanford.edu`
[2] Facebook Reality Labs, Redmond, WA 98052 USA `aliisrar@fb.com`

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compact in size and optimized for the resonance frequency to displace the skin up to 30 dB above the sensation level (SL); however, the sensation quality drops rapidly away from the resonance. Alternatively, voice coil motors (VCM) operate at a broader frequency band at the cost of increased space and power requirements. It is not clear how these additional frequencies would improve user interactions in order to justify the added cost associated with VCM over the LRA.

Information theory provides useful tools to quantify, compare, and combine performance of various sensory systems in the units of *bits*, even when different sensory channels encode information independently [7]. Previous research has approximated information transfer (IT) and IT rates (in bits/sec) to evaluate and compare the capacity of various sensory systems and display technologies in the context of human communication [10]. Rabinowitz and colleagues [11] estimated the identification scores for vibrotactile signals presented on the distal pad of the middle finger to be 1-2 bits, when the haptic signal was varied in one dimension, and 4-5 bits when the haptic signal was varied in all three dimensions (frequency, amplitude, contact area). Azadi and Jones [12] defined a small set of *tactons* that varied in frequency, amplitude, and temporal profile, showing that IT on the forearm was $\sim$2.41 bits.

Israr et al. [13] examined location and motion cues on the user's back and reported IT of 1.87 bits and 2.55 bits respectively, indicating better transmission of motion cues than static location cues. Tan et al. [14] achieved IT of up to 6.5 bits using a three-finger tactual display during a complex masking task, indicating a large set of information communicated when the dimensions of haptic perception are optimized. Finally, Kim et al. [15] showed that IT increased from 0.56 bits (vibrations only) to 2.15 bits when pressure and shear cues were also accompanied with vibrations on the wrist. In all these studies, IT was compared against various conditions to highlight that value of additional dimensions in haptics for communicating distinct signals.

The interaction space of wristband haptics is broad, and previous studies have utilized various haptic modalities to communicate messages, create realism, as well as guide and confirm users' actions with feedback on the wrist. Using a single actuator in the chassis of a watch, Pasquero and colleagues [16] associated functions of the watch to user gestures and provided haptic feedback for confirmation of user actions. Israr and colleagues [6] demonstrated a parametric approach to control the semantics of haptic feedback and used it for social purposes. Matscheko and colleagues [1] used a spatial arrangement of 4 actuators on the wrist to convey tactile messages, with 2.49 bits of motion patterns identified by users. Brown and colleagues [17] defined 27 patterns by varying three dimensions of haptic signal (rhythm, roughness, location on forearm) mapped to notification of upcoming appointments. Results showed that out of the possible 4.75 bits of information in the task, the haptic signal could only convey 2.98 bits of information – thereby saturating the tactile channels to fully communicate the intended task information.

Gupta et al. [2] used 4 VCMs at the cardinal locations around the wrist and presented concepts of tactile screen, tactile pixels, tactile pointers, and tactile targets; then, they used them in pointing, selection, and drag and drop tasks. Pezent and colleagues [4] combined squeeze with spatial vibrotactile cues to create realistic feedback during pressing, pulling, impacts, and texture. In general, signal variations in all these techniques were mapped to the feedback with no determined rules. In order to achieve the value of haptics during wristband interactions, it is hypothesized that the information transfer with haptics must be larger than the information required to complete the task, and therefore, it is necessary to determine the IT of the device as well as its salient haptic features.

III. METHOD

A. Apparatus

We built a custom wristband with six VCMs (Tectonic Audio Labs, Woodinville, WA, USA, model: TEAX13C02-8RH) located radially around the wrist and enclosed in a flexible 3D printed wristband to accommodate for various wrist sizes (Fig. 1). The signal parameters for VCMs are controlled in a series of Processing (https://processing.org/) scripts which create the user interfaces that participants interacted with during experiments. These scripts communicated via user datagram protocol (UDP) with a Max MSP patch (https://cycling74.com) that controlled the signal output. The patch then output the signal to an audio interface (MOTU UltraLite-mk3, Cambridge, MA, USA) which was connected to the wristband via a Syntacts amplifier [18] to drive the VCMs. Each signal output was limited in the software for the actuators to operate within a known safety range, and the hardware setup was connected to a separate power strip for easy emergency shut off. During the studies we actuated only two of the VCMs: one on the central dorsal side and the other on the central volar side.

B. Preliminary Study: IT for 1-Dimensional Haptic Signals

In the preliminary study, we computed the information transfer (IT) on the dorsal wrist for each of the three signal parameters (frequency, amplitude, and modulation of a sinusoidal waveform) while the other two parameters were either fixed or randomly changed. Table 1 shows the summary of main signal parameters, random parameters stimuli, and the total number of trials collected in each test session. Results of the preliminary studies yielded perceptual distance between each pair of stimulus alternatives and indication of salient parameters for the haptic signal along the test dimension.

1) Procedures: Two participants took part in the preliminary study (1 female, age $\mu = 35$, $\sigma = 12.7$). Both were right-handed, had experiences with developing various haptic feedback technologies, and provided consent to participate in the study. Before the study, rough detection threshold levels for each participant were estimated at all five test frequencies and used throughout the experiments to compensate for the variation in sensitivity level (SL) at each frequency.

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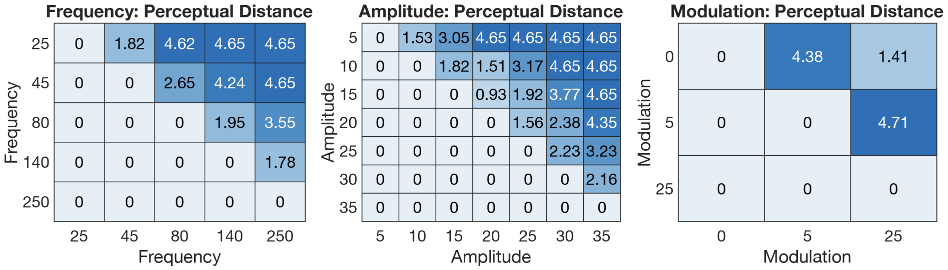
TABLE I

PRELIMINARY STUDIES: TESTING PARAMETERS AND RESULTS FOR INFORMATION TRANSFER

Comparison	**Main Parameters**	**Random Parameters**	**Total Trials**	**IT [bits]**
Frequency	25, 45, 80, 140, 250 (Hz)	2 Amplitude & 3 Durations	600	1.27
Amplitude	5, 10, 15, 20, 25, 30, 35 (dB SL) @80 Hz	∼	280	1.44
	5, 10, 15, 20, 25, 30, 35 (dB SL) @170 Hz	∼	280	1.51
Modulation	0, 5, 25 (Hz)	3 Frequencies	600	0.99



Frequency: Perceptual Distance

Frequency	25	45	80	140	250
25	0	1.82	4.62	4.65	4.65
45	0	0	2.65	4.24	4.65
80	0	0	0	1.95	3.55
140	0	0	0	0	1.78
250	0	0	0	0	0

Amplitude: Perceptual Distance

Amplitude	5	10	15	20	25	30	35
5	0	1.53	3.05	4.65	4.65	4.65	4.65
10	0	0	1.82	1.51	3.17	4.65	4.65
15	0	0	0	0.93	1.92	3.77	4.65
20	0	0	0	0	1.56	2.38	4.35
25	0	0	0	0	0	2.23	3.23
30	0	0	0	0	0	0	2.16
35	0	0	0	0	0	0	0

Modulation: Perceptual Distance

Modulation	0	5	25
0	0	4.38	1.41
5	0	0	4.71
25	0	0	0

Fig. 2. Sensitivity indices (d') for each pair of stimulus alternative tested in frequency, amplitude, and modulation comparison test sessions.

Participants wore the wristband on the left arm and tested each signal to become familiar with the stimulus set and adjust the band for comfort. Pink noise was played during testing to mask out any device and environmental noise.

In each test session, participants familiarized themselves with the UI and could test signals to get a general understanding of the range of values, but no formal training was completed. Once comfortable, they started the study. In each trial, a brief audio tone preceded the start of the haptic interval. The main parameters were randomly selected in each trial. After the haptic interval, participants recorded their response by selecting the corresponding choice on the UI (choices here were listed in text as a number ranging from 1 to the maximum number of the parameter corresponding to a low to high value). For the frequency identification tasks, two amplitudes (15 and 25 dB SL) and three durations (100, 250, 500 ms) were randomly selected for each signal, and participants were provided with 5 response choices. For the amplitude identification tasks, seven test stimuli were presented and seven corresponding response choices were provided for each of the two test frequencies. The duration of each stimulus was set to 250 ms. For the modulation identification task, three test modulations (none, 5 Hz, and 25 Hz modulation) were tested with three random carrier frequencies (45, 80, 140 Hz). The amplitude and duration were set to 25 dB SL and 250 ms, respectively. Random parameters were included in order to get a sense of how these variables affected the main parameter, while reducing the length of the experiment to reduce participant fatigue. During each trial, participants were asked to report the value of the main parameter, regardless of the values of the randomized parameters. Trials were presented in blocks of 20 trials, and participants were asked to take rest between blocks as needed. Participants completed each comparison test session in a single day.

2) Data Analysis: The results of identification tasks were expressed in terms of information transfer (IT), as in [7]. The identification scores for the two participants were pooled together and stimulus-response confusion matrices were formed for each test session. The maximum likelihood estimate of IT was calculated by using:

$$IT_{est} = \sum_{j=1}^{K} \sum_{i=1}^{K} \frac{n_{ij}}{n} log_2 \left(\frac{n_{ij} \cdot n}{n_i \cdot n_j} \right) \tag{1}$$

where, K was the number of stimulus alternatives, n was the total number of trials, n_{ij} was the number of times the joint event (Stimulus_i, Response_j) occurred, and n_i and n_j were the sum of trials for each row and column respectively. The percentage-correct scores (PC) were calculated by using:

$$PC = \sum_{i=1}^{K} \frac{n_{ij}}{n} \tag{2}$$

To determine the perceptual distance between each stimulus alternative, 2×2 stimulus-response confusion matrices were formed for each stimulus pair. Sensitivity indices for each pair was calculated by using:

$$d' = z(H) - z(F) \tag{3}$$

where the hit rate, H = N(hits)/[N(hits)+N(misses)], is the proportion of responding R_2 when S_2 was presented. The false-alarm rate, F = N(false alarms)/[N(false alarms)+N(correct rejections)], is the proportion of responding R_2 when S_1 was presented. z(.) is the inverse of a normal (Gaussian) distribution function. A sensitivity index of 3 corresponds to two highly distinct haptic signals and is saturated at 4.65 corresponding to PC of 99% [19].

3) Results: A confusion matrix was generated for each of the comparison studies, and IT was computed and reported in Table 1. Overall, participants were able to identify at least two of each frequency, amplitude, and modulation. Shorter durations, smaller amplitudes, and 25 Hz modulation signals were mostly confused. PC scores were 73%, 42%, and 83% for frequency, amplitude, and modulation test sessions, respectively. However, identification scores alone do not determine what parameter values were most salient along each dimension, therefore, we calculated the d' values between

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each stimulus alternative to determine signal parameters that were furthest apart in the perceptual space (Fig. 2).

Applying the salient criterion of $d' = 3$, the final set of haptic signals for the main experiment consists of 80 and 250 Hz, amplitudes of 10 and 25 dB SL (corresponding to barely perceptible and aggressively salient signal), and a pure and 5 Hz modulated tone with a signal duration of 500 ms.

C. Main Experiment: IT for 3-Dimensional Haptic Signals

In the main experiment, we determined the information transfer (IT) for the set of salient haptic signals to determine if: (i) the signals were intuitive and easily recognizable; (ii) if the learning of signals improve performance over time; and, (iii) if the learnt patterns could be recognized at another location on the wrist (on the volar wrist).

1) Participants: A total of 8 right-handed participants completed the study (3 females; age $\mu = 42.4$, $\sigma = 16.4$). From the demographic information, four out of the eight participants reported having high levels of experience with haptic devices (have built and programmed such devices), while the other four participants were novices (exposure to haptics only in phones and gaming consoles). Two of the experts participated in the preliminary study with significant time passing between the two studies. Before beginning the study, we explained the experimental protocol to each participant and explained the safety measures in place, including how to shut down the system. The experiment was voluntary, and participants gave a verbal consent. The studies were conducted in a home setting and one expert user was always present to set up the device and conduct experiments.

2) Procedures: Participants donned the wristband on their left arm, and adjusted the location of actuators such that the top VCM was at the central dorsal and the bottom VCM was at the central volar location. Pink noise was played during test sessions to mask out any device and environmental noise.

In order to determine which of the salient combinations of signals (based upon the results from the preliminary study) could be identified, a similar Processing script was developed to show 8 signals (2 frequencies x 2 amplitudes x 2 modulations) with visual representations for each signal (Fig. 3). Each signal had a duration of 500 ms; composed of 50 ms of ramp up, 400 ms full signal, and 50 ms ramp down. Participants were given a description of to what the images corresponded, what was meant by a high or low frequency and amplitude, as well as the difference between a pure and modulation tone. Before each phase, participants adjusted the device on the wrist and familiarized themselves with the device and UI.

There were 4 phases of the experiment: baseline, learning (with feedback), testing (dorsal side), and testing at a second location (ventral side) – all completed in a single 1 hour session. The baseline and testing phases each had 48 trials: 6 repetitions of the 8 patterns presented in a random order. The learning phase had 96 trials: 12 repetitions of the 8 patterns presented in a random order. Participants received a break after every 24 trials. During the baseline and testing phases, a brief tone was played through headphones prior to the haptic signal being displayed on the wristband. Then, participants were asked to select the image that matched the haptic signal. During the learning trials (phase 2), a similar stream of events occurred; however, after submitting their response choice, the correct answer was highlighted in green and the incorrect in red. Additionally, the correct signal was replayed while the correct signal image was highlighted to allow participants time to process this information.

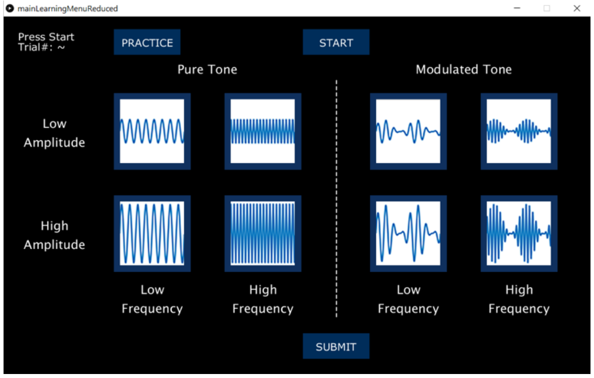

Fig. 3. Menu participants were shown during the user study. Each signal parameter is shown via an image and associated text along the sides.

TABLE II

POOLED INFORMATION TRANSFER PERCENT CORRECT

Phase	*All Participants*		*Experienced Participants*	
	IT [bits]	**PC**	**IT [bits]**	**PC**
1: Baseline	1.74	0.70	2.16	0.79
2: Learning	1.99	0.80	2.47	0.90
3: Testing	2.28	0.85	2.56	0.91
4: Testing (2^{nd} loc.)	2.03	0.78	2.36	0.86

3) Data Analysis: Identification scores, IT and PC, were computed the same way as in the preliminary studies.

4) Results: As with the preliminary study, participant responses were grouped into confusion matrices by experiment phase. From these four matrices, the Information Transfer (IT) in bits and the Percentage Correct (PC) were calculated. We also calculated the IT and accuracy for the haptically experienced group separately. Both results are shown in Table 2. Overall, there are increases in information transferred after the learning phase (comparing phases 1 and 3). However, when transferring that knowledge to a second location on the dorsal side of the wrist, there was some depreciation (phase 4 compared to 3).

To identify the effects of learning, three separate two-sided pairwise t-tests were run comparing the PC for each participant between different phases (baseline and testing on two locations). There was a significant difference in the PC between phases 1 ($\mu = 0.698, \sigma = 0.148$) and 3 ($\mu = 0.846, \sigma = 0.117$); ($t(7) = -4.20, p = 0.004, d = 1.49$). However, no significant difference was found between phases 3 and 4 ($\mu = 0.781, \sigma = 0.183$) or phases 1 and 4; ($t(7) = 1.24, p = 0.256, d = 0.44$) and ($t(7) = -1.09, p = 0.311, d = 0.39$).

In order to determine the effects of the signal parameters on the accuracy of participant's responses, a Generalized Linear Mixed Effects Model, assuming a binomial distribu-

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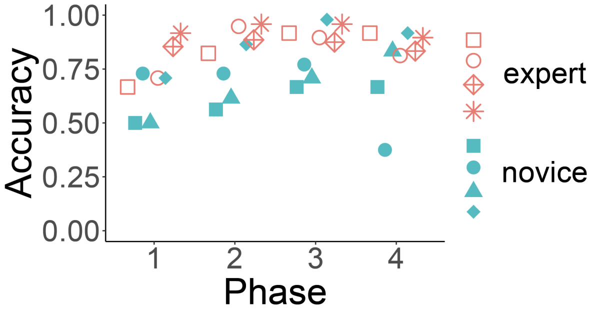

Fig. 4. Displays the average accuracy per participant (indicated by different shapes) across each phase, with colors grouping the two levels of experience.

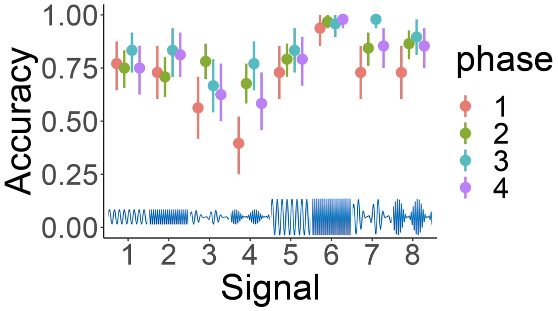

Fig. 5. Shows the mean accuracy and 95% confidence intervals for all participants, grouped by signal type. Images corresponding to each signal are shown at the bottom.

tion and logit link function, was created for the dependent variable of correct or incorrect signal selection. Within this model, random slopes were added for each independent variable: study phase, frequency, modulation, amplitude, and the interaction effects between pairs of signal variations. A random intercept was included for participants. In addition, terms were added for age and haptic experience to account for possible effects. The relationship between these variables can be viewed below:

$$response \sim phase + frequency * modulation + \\ frequency * amplitude + modulation * amplitude + \\ age + experience + (1|participant)$$

The Analysis of Deviance (Type III Wald χ^2 tests) indicates that the phase ($\chi^2(3) = 30.4, Pr(> \chi^2) < 0.001$), amplitude ($\chi^2(1) = 5.1, Pr(> \chi^2) = 0.024$), and haptic experience ($\chi^2(1) = 5.45, Pr(> \chi^2) = 0.021$) are significant. Additionally, the interaction effects between frequency and modulation ($\chi^2(1) = 12.4, Pr(> \chi^2) < 0.001$) and frequency and amplitude ($\chi^2(1) = 15.2, Pr(> \chi^2) < 0.001$) are significant as well.

IV. DISCUSSION

From the calculated pooled IT values in Table 2 and the reported t-tests, participants were able to better identify haptic signals after completing the learning phase. For the testing on the top of the wrist (phase 3), a value of 2.28 equates to 4.9 items (or approximately five of the original eight signals) identified. While there is a decline in the IT when the signals move to the secondary location on the bottom of the wrist, it is still greater than that of the baseline. Additionally, when only considering participants with high levels of haptic experience, the value does not decrease as drastically when moving to the second location – suggesting that with time novices would also be able to extend their knowledge of these signals to more locations.

Notably, the values for the "experts" (those with extensive haptic experience) change very little between the phases, possibly indicating that they have already reached peak saturation of communication via vibrotactile signal variations. To better visualize these trends, Fig. 4 shows the average correct responses for each participant across the four phases. The "novice" and "expert" participants are marked by color. This suggests that some "experts" have already been saturated in their knowledge of these signals. However, amongst "novices", most likely would have benefited from additional training, although at least one has responses mirroring those of "experts" which could be the signs of a faster learner. One novice (blue circle) performed extremely poorly at the second location. Based upon the confusion matrix, they could only differentiate between low and high amplitude signals. That user commented that it was quite difficult for them, and it is possible that gravity had pulled the actuator away from the skin reducing the contact area and thus the information transfer.

Figure 5 illustrates the overall accuracy by signal type and experiment phase. This gives a sense of what signals were most and least salient to participants. In agreement with the reported significant effects from the model, amplitude plays a distinct role in accuracy. Signals 5 through 8 on average had higher accuracy than their lower amplitude pairs (1-4 accordingly). To understand better what signals were often mistaken for one another, Fig. 6 shows the confusion matrices for each phase of the study. One clear confusion was between signals 3 and 4 which were the low amplitude, modulated tones.

The interaction effect between frequency and amplitude can be seen between most of the pairs, with higher amplitudes often being more identifiable than their lower amplitude counterparts (2 and 6 is an example of this). Similarly, the interaction effect between frequency and modulation can strongly be seen by the increased accuracy in identification of pure signals (1 and 2) compared to modulated tones (3 and 4). Overall, the modulated tones, at least those with lower amplitudes, were more difficult for participants to identify. Additionally, much of the confusion came between two frequency signals with modulation – as such it makes sense to use only one of these signal variations to maximize communication.

While efforts were made to familiarize participants with the meaning behind the images, it is also possible that the images to represent each signal in the UI had an impact on the results by influencing how participants interpreted the vibrations. However, during practice trials all participants indicated their understanding of the response menu.

V. CONCLUSION & FUTURE WORK

This methodology shows the potential for developing an understanding of the communication bandwidth of the wrist

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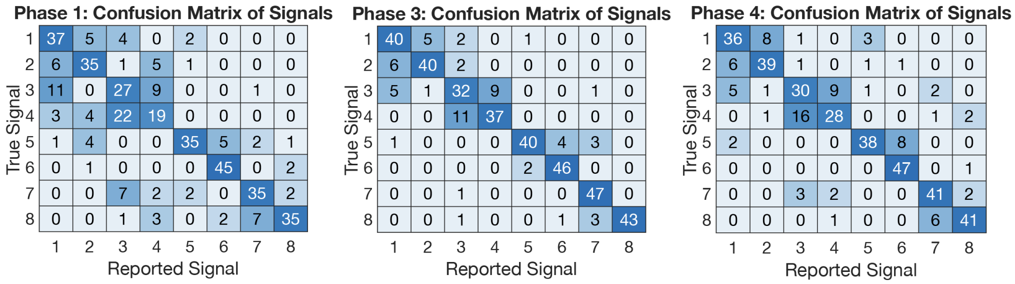

Phase 1: Confusion Matrix of Signals

	1	2	3	4	5	6	7	8
1	37	5	4	0	2	0	0	0
2	6	35	1	5	1	0	0	0
3	11	0	27	9	0	0	1	0
4	3	4	22	19	0	0	0	0
5	1	4	0	0	35	5	2	1
6	0	1	0	0	0	45	0	2
7	0	0	7	2	2	0	35	2
8	0	0	1	3	0	2	7	35

Phase 3: Confusion Matrix of Signals

	1	2	3	4	5	6	7	8
1	40	5	2	0	1	0	0	0
2	6	40	2	0	0	0	0	0
3	5	1	32	9	0	0	1	0
4	0	0	11	37	0	0	0	0
5	1	0	0	0	40	4	3	0
6	0	0	0	0	2	46	0	0
7	0	0	1	0	0	0	47	0
8	0	0	1	0	0	1	3	43

Phase 4: Confusion Matrix of Signals

	1	2	3	4	5	6	7	8
1	36	8	1	0	3	0	0	0
2	6	39	1	0	1	1	0	0
3	5	1	30	9	1	0	2	0
4	0	1	16	28	0	0	1	2
5	2	0	0	0	38	8	0	0
6	0	0	0	0	0	47	0	1
7	0	0	3	2	0	0	41	2
8	0	0	0	1	0	0	6	41

Fig. 6. Confusion matrices for baseline, testing (dorsal), and testing (volar) for all participants combined.

from signal variations utilizing Information Transfer. From the study, participants were able to learn haptic signals, with many experts understanding the signals from the onset. It also showed that information can be somewhat transferred to a secondary, untrained location on the wrist, for which users had no training, but with some depreciation. While performance varied by signal, the high frequency signal with high amplitude and no modulation had the highest accuracy of identification. Nevertheless, with very limited amounts of training, we determined that a single vibrotactile actuator was capable of communicating at least five varied signals or approximately 2.28 bits of information.

More questions need to be addressed to fully apply these concepts in user applications. This study allowed participants to focus completely on the task of identifying the presented signals, but in reality, users are receiving information from a variety of locations in a multitude of modalities. While we are able to report upon generally how many signal variations users can learn, we are unable to comment on how that value might change or degrade once users are in a more complicated and distracting situation – that likely would be the case when using a wrist worn haptic device. As such, future work will examine questions related to receiving a stream of information simultaneously as well as giving users a primary non-haptic task.

Additionally, there is the opportunity to explore multi-actuator feedback. In this study, we only used two of the six actuators in our device. Using the same concept of Information Transfer, we can work to identify an upper bound for the number of actuators that can be perceived as useful and singularly identifiable. This also opens the door to exploring sensory illusions and motion patterns, beyond just a single vibration at a time. These types of patterns would increase the range of sensations and might offset the additional cost of more actuators.

Finally, future efforts can work to apply the knowledge about communication bandwidth gained here in specialized applications. We are interested in taking these principles and breaking down XR scenarios into bits of information that could be communicated through single or multiple actuators with signal variations. Overall, the framework for testing and analysis presented here can be utilized to begin quantifying the communication bandwidth of the wrist.

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