Body-Mounted Vibrotactile Stimuli: Simultaneous Display of Taps on the Fingertips and Forearm

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***Abstract*—In this article, we present a body-mounted tactile display to deliver haptic feedback to the forearm and user-initiated haptic feedback to the fingertips. The display mounts two vibrotactile actuators on the forearm, leaving the user's hands free for manipulation tasks when the hands are not interacting with the tactile display, while also exploiting the tactile sensitivity of the fingertips when needed. We test the effectiveness of the display using paired vibrotactile taps sensed through the forearm and the fingertips, either separately or simultaneously. We measure the ability of participants to identify the vibrotactile taps. The results show that mounting the device on the forearm, so that the participant touches the forearm-mounted device with their fingertips receiving feedback to both locations simultaneously, decreases performance relative to mounting on the fingertips unless large amplitudes are used. We also test the accuracy with which participants identified different numbers of vibration taps (4, 8, 16, and 25 signals). The results show that as the number of signals changes, participant accuracy is not different when stimulating the fingertips alone compared to stimulating the fingertips and forearm together. We conclude with an example of a portable and wearable vibration display, and discuss future use cases of such a display.**

***Index Terms*—vibration feedback, simultaneous signals, vibration display, wearable devices.**

I. Introduction

There is a long history of distributed tactile displays [1], ranging from small fingertip displays [2] to large displays for bimanual interaction [3]. Burgeoning applications in virtual reality and mobile devices have increased interest in wearable haptic devices [4]. Most prior work has focused on the fingers and hands, with good reason – mechanoreceptors are more dense in the glabrous skin of the hands and feet than in hairy skin (such as on the arms), so touch is easier to localize on glabrous skin [5]. Active sensing using the fingers and hands maximizes information transfer for a given task [6]. However, fingertip-mounted and hand-mounted devices inherently impede manual interactions with the the environment.

Researchers have investigated body-mounted displays, for example forearm-mounted displays [7], as an alternative way to communicate information. However, forearm-mounted displays rely on passive tactile feedback, and localizing signals can be difficult [7]–[9]. To address limitations of both fingertip and forearm displays in communicating information, we propose a forearm-mounted haptic device with a display area that is easily accessible to the fingertips of the opposite arm.

The device provides haptic feedback locally to the forearm, where it is mounted, and, by exploring the device with the hand of the opposite arm, a user can also receive tactile feedback on their fingertips. Mounting the device on the body exploits the sensitivity of the fingertips while only impeding manipulation tasks when the user is purposely using their fingertips on the tactile display. This device architecture is intended to be used with types of haptic signals for which the fingertips have definitively been shown to be more sensitive than the forearm, e.g. vibration [10].

Providing haptic signals that can be felt at two locations on the body makes possible layered communication strategies that involve multiple locations simultaneously or stimulate different locations at different times. For example, we can display an initial haptic signal, such as a short vibration to the arm ("notification signal"), to call a user's attention to a more complex touch message that can then be identified by the fingertips ("information signal"), without requiring visual attention. When the user chooses, they can feel the device with their fingertips to receive the message. This is a key feature of this work: signals felt passively on the skin of the arm can be perceived with greater accuracy and detail by using the fingers of the opposite hand. Using this communication model, it is possible to send a notification message and then a subsequent information message, or have the notification message and information message be the same. In both cases the information message will stimulate both the fingertips and forearm simultaneously. We are interested in understanding whether stimulating the fingertips-and-forearm together influences user performance compared to stimulating the fingertips alone. As a first step toward developing more complex multi-site communication signals, we conducted two studies to assess participant accuracy with a set of vibrotactile taps designed with this device paradigm in mind.

Although many types of haptic feedback (including skin slip [11], normal indentation [12], etc.) could be used for a

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body-mounted tactile fingertip display, we chose vibration feedback because it is a well-studied form of haptic feedback, with psychophysical properties that are widely reported in the literature, e.g. [13]. However, it is not clear that vibration feedback at multiple locations will be effective because of masking, in which the absolute threshold of vibration at one location increases when vibrations are applied simultaneously at another location [14], [15]. Little research has been done to investigate how masking affects participant accuracy when performing specific tasks. Tan *et al.* [16] performed experiments revealing that forward, backward, and sandwiched masking have a negative effect on participant accuracy when identifying vibration cues unless there is sufficient time between signals. For our proposed display, it is also important to test the effects of concurrent stimuli and the effects of simultaneous stimulation on multiple contralateral locations on the body. In this paper, we compare the accuracy of participants identifying signals felt at single locations versus simultaneously at multiple locations in order to understand how much information is captured by the participants, and to identify ways to account for perceptual effects.

II. Related Research

Vibration is a commonly used form of wearable haptic feedback [13] that can convey a wide variety of meaningful signals. Vibration feedback is most commonly achieved using eccentric rotating mass motors; the motors have small form factor and low power consumption, but frequency and amplitude are coupled – so control over their output is limited. In contrast, voice coil actuators and linear resonant actuators are used to create specific vibration wave forms in which frequency and amplitude are required to be decoupled [17]. By arranging multiple actuators in a specific spatial configuration, a large number of actuation signals can be rendered.

Developing a large and intuitive set of signals that can be distinguished and remembered with high accuracy is a difficult challenge [17]–[19]. When the information is simple and can be encoded within a few haptic signals (forward, back, right, left navigation signals, for example), simple binary vibration signals can be sufficient. To communicate more complex information, a higher information transfer rate is required. Although information transfer rates can be increased simply by presenting low-information signals at a faster rate, studies have shown that it is more effective to present information-rich signals at a slower rate [20], [21]. In other words, the key to increasing information transfer through the haptic channel is not to increase the presentation *rate* of signals, but rather to increase the information *content* of each cue [21].

Many types of vibration signals have been developed for both wearable displays and desktop tactile devices. Among wearable displays, Barralon *et al.* developed a waist belt with 6 tactors and designed 36 unique stimuli [22] as well as tested 4 different rhythm schemes each with 20 signals with the belt [23]. The Edgevib, a wrist worn wearable vibration device, was able to communicate the alphabet and numbers [17]. Using a desktop vibration platform, Tan *et al.* presented a set of 90 vibrotactile signals that are location dependent and found they could transfer 12 bits/s of information [24]. Additionally, Ternes *et al.* developed a set of 84 distinguishable vibrotactile signals that use "rhythms," which they defined as regular and repeated vibration patterns [19]. Lipari *et al.* investigated dense arrays of vibrotactors that can be explored by the fingertips or hand [25].

When designing our device, we considered the human perceptual limits of the fingertips and forearm, which are well studied in the literature. The principal mechanoreceptor that is most sensitive to high frequency vibrations is the Pacinian corpuscle, whose sensitivity is in the range of 10-500Hz [13]. Pacinian corpuscles display spatial and temporal summation, where the sensitivity to the stimulus is proportional to contact area, and the stimulus accumulates over time until the receptors saturate [13]. If the amplitude of the vibration is large enough, other mechanoreceptors will also respond to the vibration stimuli [26].

The hairy skin of the forearm is less sensitive to vibration than the glabrous skin of the fingertips; the skin of the volar forearm has a perception threshold approximately 10 dB higher than the glabrous skin of the hand at 125Hz and 250Hz [10], [27]. Furthermore, localization of vibration signals on the forearm is more accurate when the signals are delivered closer to the wrist or elbow, and worse when delivered near the center of the forearm, further from the joints [8]. Summers *et al.* [28] demonstrated that even though fingertips are more sensitive than the forearm, task performance on the forearm can be better than the fingertips if signal amplitudes are increased to compensate for perception threshold differences and if the signal set is intuitively designed [28]. These observations informed the mounting and spacing of the vibrotactile actuators used in our studies.

In our work, participant performance is assessed by metrics such as accuracy, recall, and precision. Information transfer from haptic modalities is commonly measured by static information transfer (IT). The quantity IT, measured in bits, estimates the amount of information transferred, given uncertainty. The maximum likelihood estimate of the IT is given by the following formula presented by Tan *et al.* [21]:

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

where each of the k total stimuli is denoted S_i, $1 < i < k$, and each response is denoted R_j, $1 < j < k$. We define n as the number of collected trials, and n_{ij} as the number of times the stimulus-response pair (S_i, R_j) occurs. Finally, n_i and n_j are the row and column sums respectively, $n_i = \sum_{i=1}^{k} n_{ij}$ and $n_j = \sum_{j=1}^{k} n_{ij}$. All of the values used when calculating IT_{est} can be derived using a confusion matrix of the stimuli and responses.

Studies have measured accuracy and information transfer at the forearm and fingertip, and devices have been designed to deliver haptic signals to multiple fingers (the thumb, index, and middle fingers) [24], [28], [29]. However, there have been

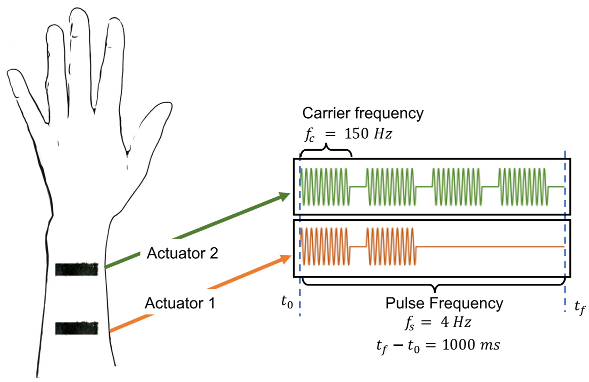

Fig. 1. Signals are played simultaneously to Actuator 1 and Actuator 2. They begin at time t_0 and end at time t_f. The carrier frequency, f_c, is the frequency of the sinusoidal pulse. The pulse frequency, f_s is the frequency at which pulses occur in the signal.

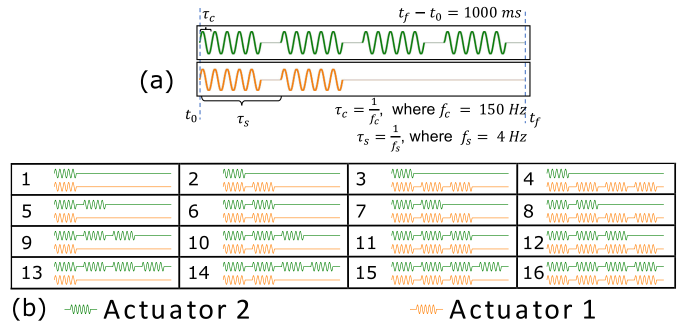

Fig. 2. (a) A magnified and labeled illustration of one example signal (Signal 14). The carrier frequency of the vibration signal, f_c, was 150 Hz. The pulse frequency, f_s, was 4 Hz. The entire duration of pulse, $t_f - t_0$, was 1000 ms. (b) All 16 signals in the set played to the participants.

no investigations, to the best of our knowledge, on the accuracy of simultaneous vibration signals to the fingertips and forearm with multiple actuators. To explore this concept, we demonstrate here a novel mechanism for delivering information via a tactile display mounted on the forearm that can be optionally explored by the fingertips.

III. Vibrotactile Taps

To understand participant performance when feedback was provided to the fingertips-only, to the fingertips-and-forearm, and to the forearm-only, we designed hardware and a set of signals that could be applied to the forearm and multiple fingers of the hand.

A. Paired Vibrotactile Taps Design

Through pilot testing, we determined that rhythmic temporal-spatial signals were intuitive for participants to learn. Brown *et al.* introduced the concept of rhythms and found that they could communicate three distinct rhythm tactons with an accuracy of over 90% [30]. Multiple rhythm schemes have been shown to be noticeable and distinguishable [19], [30]. In our experiment, we modified the rhythm scheme by Ternes *et al.* [19] so that two actuators simultaneously send two separate rhythms to the participants (Fig. 1). For example, the first actuator sends a rhythm from a predetermined set. The second actuator sends an independent rhythm from the same set, so using two actuators allows for multiplexing information through the haptic channel in short periods of time. Given that the rhythm (beat) of the signal does not change, we instead call our signals "taps".

The simultaneous taps are two signals that are the same until, at some point, one of the actuators turns off. Each pulse lasts a total of 250 ms and is composed of a 187.5 ms sine wave played at 150 Hz and is followed by a 62.5 ms latency period (Fig. 2). The pulse and latency periods are the same as those used by Ternes *et al.* [19]. There are four different signals: one pulse, two pulses, three pulses, and four pulses, as shown in Fig. 2. When the signals are played on two actuators there are 16 separate signals, not 8, because the spatial location of the actuator intrinsically encodes information. In this way, if there were perfect transfer of the signals, we could achieve a maximum static IT of 4 bits.

Tan *et al.* noticed that simultaneous signals sent to different fingers with the same and different wave forms were hard to differentiate [24]. Additionally, Gallace *et al.* showed that numerosity, or increasing the number of simultaneous signals, reduces participant accuracy [31]. Despite a potential decrease in accuracy, we chose to display the signals using two actuators simultaneously because this allowed us to dramatically increase the number of possible signals that could be displayed within a 1-second interval without shortening the length of the pulses.

B. Hardware

The gold standard for fingertip tactile displays are desktop-mounted devices that allow for extremely repeatable stimulation. Instead of a desktop-mounted display, we created a body-mounted display (henceforth called the fingertips-and-forearm condition) and compared it to a fingertips-only condition, where only the fingertips were stimulated. We also considered a forearm-only condition because the forearm has a larger two-point discrimination threshold [32] and vibration perception threshold [10] than the fingertips, and to quantify how much adding fingertips sensing to forearm sensing can enhance participant performance for signals of the same amplitude.

The experimental setup was composed of two vibrotactile actuators, a desktop platform for the actuators, and the electro-mechanical architecture. The two vibrotactile actuators were Haptuator Mark II voice coil motors, shown in Fig. 3, that are controlled using signal outputs from a Sensoray 826 PCI card. Most traditional voice coil motors and electro-mechanical motors move normal to the surface of the skin. However, the Haptuator Mark II actuators are rectangular prisms designed to move parallel to their long axis. This allowed us to deliver the same tangential vibration signal to both the fingertips and the forearm.

In the fingertips-only condition, the participant rested their dominant arm on a foam cushion, and their index and middle fingers were attached to two actuators using 0.5 in by 3 in

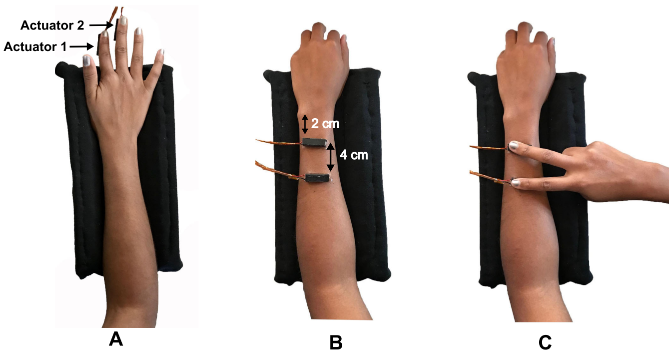

Fig. 3. The study was conducted with three conditions. Participants receive feedback to (A) the fingertips-only, (B) the forearm-only (C) and the fingertips-and-forearm. The tactors are mounted to the fingers and forearm using double sided tape, as shown in (A). Pairs of Haptuator Mark II actuators are shown in each image.

double-sided tape (Fearless Tape) (Fig. 3 A). We selected the index and middle fingers because the fingers are similar in length, and it was comfortable to maintain the required hand posture throughout the experiments. In the fingertips-and-forearm condition, the actuators were mounted to the non-dominant forearm, which rested in the foam cushion, and the index and middle fingers using double-sided tape (Fig. 3 C). In the forearm-only condition, the actuators were mounted to the non-dominant forearm with double-sided tape and the forearm rested on the cushion (Fig. 3 B). When placed on the forearm, the first actuator was placed 2 cm away from the wrist (designated by the ulna styloid), shown in Fig. 3 B. The tactors were spaced 4 cm apart based on guidelines developed by van Erp *et al.* for delivering vibrotactile signals [33], so participants with various hand sizes could comfortably place their index and middle fingers on either actuator. Actuator 2 was always mounted closest to the ulna styloid and felt by the middle finger, see Fig. 1. Actuator 1 was always mounted closer to the elbow and was always felt by the index finger.

A Kistler 8614A accelerometer was used to calibrate the acceleration amplitudes of the sinusoidal taps, and to confirm that the delivered taps were the same both when mounted on the desktop platform and when mounted on the forearm. The actuators were calibrated while in contact with skin, to have a maximum acceleration of 1.5 g (14.7 $\mathrm{m/s^2}$), 3 g (29.4 $\mathrm{m/s^2}$), and 6 g (58.8 $\mathrm{m/s^2}$). The approximate power of the vibration, with respect to the absolute thresholds Summers *et al.* report in [28], is calculated for the three conditions and is reported in Table I. We selected amplitudes above the comfortable stimuli range reported by Van Erp *et al.* [33] for the fingertips in order to observe the effect of amplitude while also achieving reasonable performance in the forearm-only condition. Additionally, the amplitude range allows us to compare the fingertip-only and forearm-only performance when the perceived intensity for the two locations are similar. Participants were given multiple breaks and no participant mentioned discomfort during the studies. To control the amount of normal force a participant applied to the actuators, we requested that participants rest their weight on the cushion, and not the actuators, throughout the experiment. We observed during a pilot study that it is more comfortable for the participant to rest the weight of their hand on the cushion than on the actuators, so participants were not asked to maintain an uncomfortable posture. We measured the force of the index finger of an exemplar participant in this pose over a 30-second period to be 0.094 ± 0.001 N.

TABLE I
DECIBELS SENSATION LEVEL ($\mathrm{dB_{SL}}$) FOR FOREARM AND FINGERTIPS CALCULATED BASED ON THEIR RESPECTIVE ABSOLUTE THRESHOLDS. THE REFERENCE THRESHOLDS USED ARE 0.5μM FOR THE FINGERTIP AND 1.6μM FOR THE FOREARM [28]. THE DISPLACEMENTS (IN μM) OF THE ACTUATORS ARE CALCULATED USING THE MEASURED AMPLITUDE OF THE SINUSOIDAL SIGNALS. THE ($\mathrm{dB_{SL}}$ IS CALCULATED USING $20\log_{10}(P/P_0)$ WHERE P IS THE DISPLACEMENT AND P_0 IS THE REFERENCE THRESHOLD

Amplitude (g)	Fingertips ($\mathrm{dB_{SL}}$)	Forearm ($\mathrm{dB_{SL}}$)
1.5	30	20
3	36	26
6	42	32

IV. Study 1: Amplitude and Location

We performed a study with 18 right-handed participants, 8 male, 10 female, aged 19-30, to determine participant accuracy for the set of taps. Users identified the taps shown in Fig. 2 for three amplitudes (1.5g, 3g, and 6g) and three mounting conditions (fingertips-only, fingertips-and-forearm, and forearm-only). The amplitudes of the signal were selected such that the fingertips-only condition and forearm-only condition have the same amplitude signal, not necessarily the same perceived intensity. The Stanford University Institutional Review Board approved the experimental protocol and all participants gave informed consent (Protocol #22514).

A. Methods

Each participant sat at a table in front of a computer and used their left (non-dominant) hand to input their responses via mouse click to a simple GUI. The non-dominant hand was used because each participant receives feedback to their dominant hand during conditions with the fingertips. In the fingertips-and-forearm condition, the mouse was placed under the participant's non-dominant hand that rested on the arm rest. In each trial, the participant felt the signal and selected and submitted their response. When responding, the participant selected the number of pulses felt by each Actuator 1 and Actuator 2. We allowed the participant to initiate the signal to ensure that they were prepared to receive the cue. For all trials, the participant wore noise cancelling headphones playing brown noise to block sound produced by the voice coil motors.

The study was conducted over one-hour sessions on each of three days, spanning no more than a seven-day period. Each day, the participants received haptic feedback in one of three conditions: fingertips-only, forearm-only, or fingertips-and-forearm. The six possible permutations of the order of these conditions were pseudo-randomized and balanced across the participant pool to mitigate ordering effects. For each condition, participants experienced a training session in which they received each of the 16 signals at each possible amplitude in a random order. Unlike

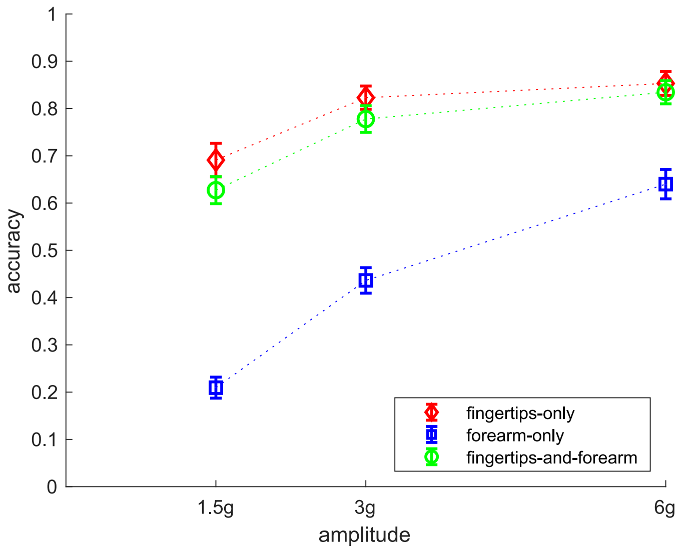

Fig. 4. Average accuracy and standard error for each condition across participants. The forearm-only condition performed significantly worse than the other two conditions. The dashed line is simply a visual aid.

Summers *et al.* [28], we did not implement amplitude compensation in the forearm-only condition, where the forearm vibration amplitude could have been modulated to be perceptually equal to the fingertips' amplitude, because we wanted to measure how participant performance changed when the amplitude was the same but the fingertips were used.

During the testing phase of the study, participants identified the signal three times for each amplitude. For each condition, the participants experienced each pair of signals three times in a randomized order. This amounted to 144 experimental trials per condition and 432 experimental trials per participant. The participants were given a 1-minute break every 48 trials. We collected data from 18 participants for a total of 7776 trials. The participants completed a post-study questionnaire in which they were asked for which experimental condition they felt the most and least confident in their responses and what strategies they used to distinguish the signals.

B. Data Analysis

For each trial, the participant was either correct or incorrect; consequently, we fit a general linear mixed-effects model assuming a binomial distribution and a logit link function to evaluate differences between experimental conditions. We created a three-level factor for location (H_{loc}), a three-level factor for amplitude (H_{amp}), and a multi-level factor for their interaction term ($H_{loc:amp}$). We also created an eighteen-level variable for participant, $H_{participant}$, so it could be included as a random effect. For each factor we fit a coefficient, β.

$$D_v = \beta_{loc} H_{loc} + \beta_{amp} H_{amp} + \beta_{loc:amp} H_{loc:amp} + (1|H_{participant}). \quad (2)$$

C. Results

The average accuracy for all participants for all conditions is shown in Fig. 4. The Analysis of Deviance (Type II Wald χ^2 tests) show that location ($\chi^2(2) = 855.7$, $Pr(> \chi^2) <$ 2.2e-16), amplitude ($\chi^2(2) = 448.96$, $Pr(> \chi^2) <$ 2.2e-16), and their interaction term ($\chi^2(4) = 44.24$, $Pr(> \chi^2) <$ 5.7e-09) are all significant. Tables II and III show the interaction effects. The confidence intervals (CI) and standard error (SE) are reported in the tables.

TABLE II
PAIRWISE COMPARISONS GIVEN ON THE RESPONSE SCALE, USING THE TUKEY METHOD, AND SORTED WITH RESPECT TO AMPLITUDE. P-VALUES FOR STATISTICALLY SIGNIFICANT PAIRS ARE SHADED IN GRAY

1.5g					
contrast	**ratio**	**SE**	**low CI**	**high CI**	**p-value**
finger, arm	0.108	0.0123	0.0831	0.142	<.0001
finger, finger/arm	0.743	0.0774	0.5822	0.948	0.0121
arm, finger/arm	6.852	0.7645	5.2755	8.9	<.0001
3g					
contrast	**ratio**	**SE**	**low CI**	**high CI**	**p-value**
finger, arm	0.154	0.0177	0.1177	0.202	<.0001
finger, finger/arm	0.746	0.0917	0.559	0.995	0.0451
arm, finger/arm	4.839	0.5285	3.7461	6.251	<.0001
6g					
contrast	**ratio**	**SE**	**low CI**	**high CI**	**p-value**
finger, arm	0.293	0.0356	0.2203	0.389	<.0001
finger, finger/arm	0.865	0.1164	0.6313	1.186	0.5294
arm, finger/arm	2.954	0.3484	2.2409	3.895	<.0001

TABLE III
PAIRWISE COMPARISONS OF PARTICIPANT PERFORMANCE GIVEN ON THE RESPONSE SCALE, USING THE TUKEY METHOD, AND SORTED WITH RESPECT TO LOCATION. P-VALUES FOR STATISTICALLY SIGNIFICANT PAIRS ARE SHADED IN GRAY

fingertips-only					
contrast	**ratio**	**SE**	**low CI**	**high CI**	**p-value**
1.5g, 3g	2.14	0.252	1.622	2.82	<.0001
1.5g, 6g	2.69	0.331	2.014	3.59	<.0001
3g, 6g	1.26	0.167	0.921	1.72	0.1972
forearm-only					
contrast	**ratio**	**SE**	**low CI**	**high CI**	**p-value**
1.5g, 3g	3.04	0.335	2.347	3.93	<.0001
1.5g, 6g	7.26	0.812	5.583	9.43	<.0001
3g, 6g	2.39	0.241	1.885	3.03	<.0001
fingertips-and-forearm					
contrast	**ratio**	**SE**	**low CI**	**high CI**	**p-value**
1.5g, 3g	2.15	0.236	1.657	2.78	<.0001
1.5g, 6g	3.13	0.368	2.375	4.12	<.0001
3g, 6g	1.46	0.182	1.089	1.95	0.007

In all conditions, the participants were able to correctly determine the largest number of pulses in any pair of taps with high accuracy, as shown in Fig. 5. For example, if we sent one pulse to Actuator 1 and four pulses to Actuator 2, the largest number of pulses would be four pulses. At 1.5g, participants determined the largest number of pulses with the following accuracy and standard error: 0.98 ± 0.03 for the fingertips-only, 0.97 ± 0.06 for the fingertips-and-forearm, and 0.65 $\pm$

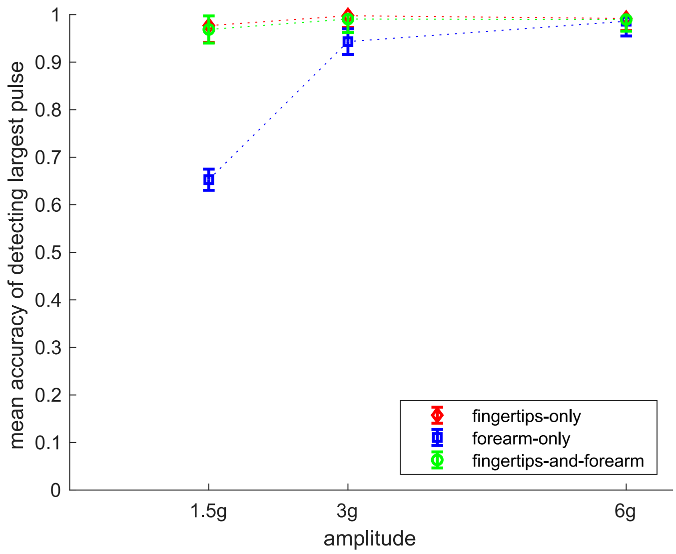

Fig. 5. The maximum number of pulses is defined as the maximum number of pulses sent to Actuator 1 and Actuator 2. The plot shows that, at high amplitudes, participants can detect the signal with the maximum number of pulses with high accuracy, even in the forearm condition. The error bars represent the standard error.

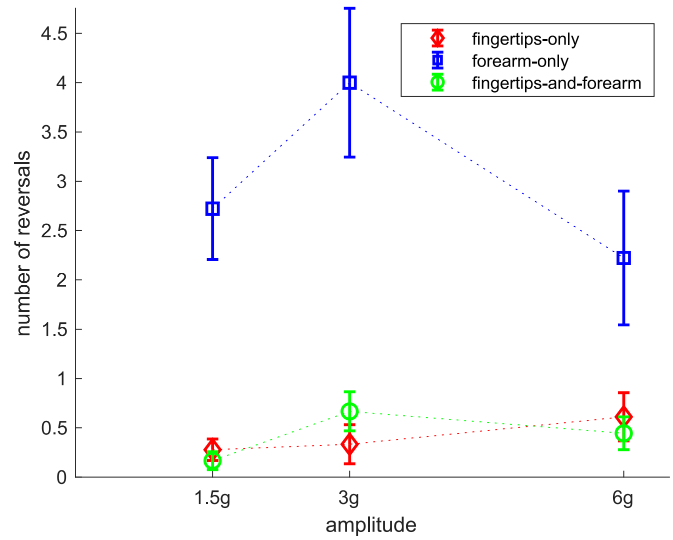

Fig. 6. Mean number of reversals for all conditions. A reversal occurs when the signals are switched between actuators. More reversals occur in the forearm-only condition compared to the other conditions. There are 48 trials in each condition. The error bars represent the standard error.

0.22 forearm-only condition. However, when the amplitude is 6g, the average accuracy and standard error are 0.99 ± 0.02 for the fingertips-only, 0.99 ± 0.02 for the fingertips-and-forearm, and 0.99 ± 0.02 for the forearm-conditions. These results show that participants can determine 2 specific bits of information contained within the signal with high accuracy.

When the signals were switched between actuators, we say that a participant "reversed" a signal. Reversal is a phenomena that has been previously observed in the literature when simultaneously stimulating two locations [29]. For example, a participant responded that the signal was one pulse to Actuator 1 and two pulses to Actuator 2, while the stimulus was actually two pulses to Actuator 1 and one pulse to Actuator 2. We fit a general linear mixed-effects model to the number of reversed signals, as shown in Fig. 6, assuming a Poisson distribution. We used the same model shown in Eq. 2; however, the number of reversed trials was used as the dependent variables (D_v in Eq. 2). The results showed that location ($\chi^2(2) = 124.7633$, $Pr(> \chi^2) < 2.2\text{e-}16$) and amplitude ($\chi^2(2) = 9.29$, $Pr(> \chi^2) = 0.01$) were significant, but their interaction term ($\chi^2(4) = 8.47$, $Pr(> \chi^2) = 0.076$) was not. Pairwise comparisons of the number of reversals using the Tukey method showed that, for all amplitudes, the fingertips-only and forearm-only conditions and the fingertips-and-forearm and forearm-only conditions were significantly different ($p < 0.0001$). The fingertips-only and fingertips-and-forearm conditions did not have a significantly different number of reversals ($p = 0.99$). No pairwise comparisons of amplitude were significantly different ($p > 0.05$). The results show that participants more frequently reversed the signals sent in the forearm-only condition, as shown in Fig. 6.

The confusion matrix for all signals under all conditions in Fig. 7 A illustrates the different ways in which participants confused the signals. We also show the confusion matrices for all locations and amplitudes to illustrate how participants confuse signals across experimental conditions (Fig. 7 B). The IT_{est} values were calculated from the confusion matrices for each condition and are shown in Table IV. The IT_{est} and standard deviation for all conditions combined was 3.12 ± 0.57.

In the post-survey questionnaire, seven out of eighteen participants reported feeling most confident in their answers for the fingertips-only condition. Nine out of eighteen participants reported feeling equally confident about the fingertips-only and the fingertips-and-forearm conditions. All participants responded that they felt the least confident about their responses in the forearm-only condition.

D. Discussion

1) Increasing Amplitude Reduces Effect of Body-Mounting Device: The results demonstrate that when amplitude is accounted for, it is possible to communicate information to the fingertips with a body-mounted device with similar effectiveness as with a fingertip-mounted device, while leaving the hands unconstrained. This is evidenced by the result that there is no statistically significant difference between the ratio correct for the fingertips-only and fingertips-and-forearm conditions in the 6g amplitude condition, as shown in Table II.

Overall, the amplitude of the vibration has a strong measured effect on participant accuracy. At lower signal amplitudes, body-mounting the device can have a statistically significant negative effect. This result, while revealing the limitations of body-mounted vibration displays compared to desktop-mounted or fingertip-mounted vibration displays, demonstrates a method by which the decrease in participant accuracy can be minimized. Namely, the decrease in participant accuracy can be minimized by increasing the signal amplitude. However, one must note that the power of the vibration signals delivered to the fingertips at 1.5g, 3g, and 6g, and to the forearm at 6g, as shown in Table I, are already

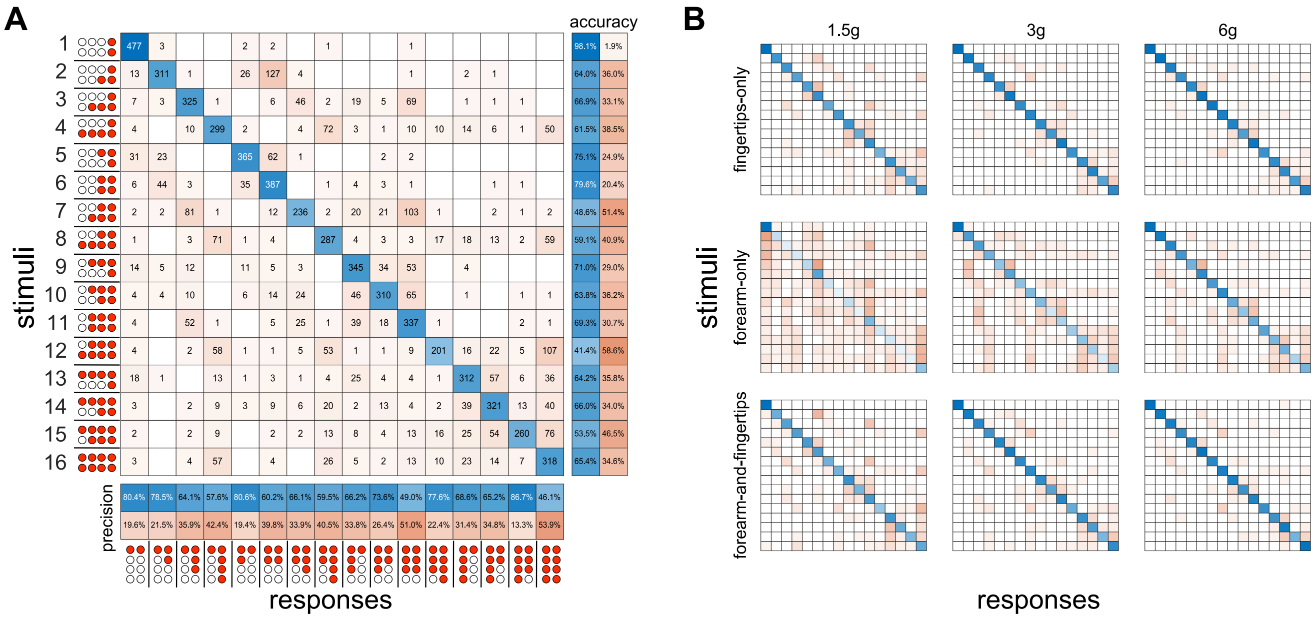

Fig. 7. (A) Confusion matrix of all signals for all participants under all conditions. The stimuli sent to the participant S_i, are pictured along the vertical axis. The responses, R_i, are listed along the horizontal axis. The responses are the signals that the participants guessed and the stimuli are the signals that were actually sent to the participants. All test trials across all participants are pictured. The matrix shows where common confusion occurs in the set of signals. The darker values indicate where stimuli were predicted with high frequency. Precision values are provided along the bottom of the confusion matrix. The values in blue represent the precision, and the values in orange represent 1 minus the precision. Precision is calculated by dividing the total correct identifications, where the stimuli and response are the same (diagonal entry for that response), by the total instances where that response was given (the column sum for that response). (B) Confusion matrices for all conditions. The figure provides a visual representation of which signals were confused for each condition. The signal order along the axes is the same as (A) and the color mapping is the same for (A) and (B).

larger than what has been shown to be comfortable for participants [33]. This indicates that there may exist a trade-off between participant accuracy and participant comfort.

2) Body-Mounting Effect on Participant Accuracy is Small: The difference in accuracy between the fingertip-and-forearm (63% at 1.5g and 78% at 3g) and fingertips-only conditions (69% at 1.5g and 82% at 4g) is 6% at 1.5g and 4% at 3g and may be negligible for some applications. To maximize participant performance, it may be beneficial to explore other avenues, such as applying different types of haptic feedback to the forearm versus the fingertips. However, additional research needs to be conducted to completely understand whether using different feedback, such as the multi-modal signals in [34], at the fingertips versus the forearm is advantageous.

Layered communication implies that the fingertips would actively explore a body-mounted device, which could influence the dynamics of the device. The force of the fingertips on the actuators was measured for one participant in the fingertips-and-forearm condition and was 0.094 +/- 0.001 N over a 30-second period. This value is very small, but nonzero, such that damping of the actuators could be occurring in the fingertips-and-forearm condition, decreasing the signal amplitude and consequently the perceived intensity. However, additional factors could be playing a role. For example, the results of [35] show, using the same Mark II actuators, that when more normal force is applied to the tactors, the detection threshold decreases. Consequently, a combination of factors may result as participants interact with a device. Future work will explore how these effects could be mitigated by incorporating closed-loop feedback to account for system dynamics.

3) Fingertips Improve Participant Accuracy Without Increasing Power Consumption: In instances where the forearm accuracy is low because of narrow inter-tactor spacing or small signal amplitude, our results illustrate that including fingertips in a wearable display could improve participant performance compared to only delivering feedback to the forearm. Our results support the idea that attaching separate fingers to actuators improves localization and overall performance, reinforcing work performed by Culbertson *et al.* [36].

Additionally, participants do not frequently confuse signals by location when the fingertips are involved. Fig. 6 shows the ratio of instances where participants reversed the signals to Actuator 1 and Actuator 2. In the forearm-only condition there is a significantly higher ($p < 0.0001$) number of reversals (2-4 reversals) than when the fingertips are involved (0-1 reversals). The overall number of reversals is small, but accounts for 6% of the error in the forearm-only condition. Overall, we confirm that it is possible to design a haptic device that uses the tactile superiority of the fingertips to increase the information encoded by a forearm-mounted device. Stimulating the fingertips with the forearm-mounted device improved user performance compared to only stimulating the forearm, indicating that it may be possible to mount the fingertip-display to other locations on the body, such as the upper arm, waist, or back, and achieve similar performance to mounting on the forearm.

TABLE IV
THE MEAN IT ESTIMATE AND STANDARD DEVIATION FOR ALL CONDITIONS

IT_{est} (bits)			
	1.5 g	3 g	6 g
fingertips-only	3.20 ± 0.34	3.50 ± 0.29	3.60 ± 0.26
forearm-only	2.06 ± 0.46	2.61 ± 0.36	3.07 ± 0.32
fingertips-and-forearm	3.09 ± 0.28	3.41 ± 0.30	3.54 ± 0.26

4) Forearm Performance and Implications for Layered Communication: For the same acceleration amplitude, the ability to interpret haptic signals is reduced in the forearm-only condition compared to conditions that involve the fingertips (Table II). This is consistent with our hypothesis because the forearm is less sensitive than the fingertips to vibration stimuli of the same amplitude [10]. We show that the errors in the forearm-only condition could be lowered by increasing the amplitude of the signals. It may also be possible to reduce errors by moving the actuators further apart, or by increasing the stimulus onset asynchrony [26], [29]. Our results show that by increasing the amplitude in the forearm-only condition (64% at 6g), participant accuracy approaches that of the fingertips-only and fingertips-and-forearm conditions (69% accuracy and 63% accuracy at 1.5g respectively), see Fig. 4. Given the powers calculated in Table I, we see that the power on the fingertips at 1.5g is approximately 30 $\mathrm{dB_{SL}}$, and the power for the forearm at 6g is approximately 32 $\mathrm{dB_{SL}}$. Thus, our result is consistent with the results from Summers *et al.* [28], as we both show improved performance of the forearm with amplitude compensation.

Our results show that at high signal amplitude, the device could perform well without the fingertips involved at all. A drawback is that the vibrations at these high amplitudes are audible and consume more power, which is often limited in a wearable device, to communicate the same amount of information. At 1.5g the sound is very quiet, but at 3g and 6g the sound is clearly audible, even in noisy environments. This means that discrete haptic communication could be infeasible if only amplitude compensation is used.

5) Insights for Layered Communication: All participants have high accuracy when detecting the maximum number of pulses (Fig. 5). Additionally, the results demonstrate that certain signals are perceived similarly well at different locations (Fig. 7 B). For example, the signal composed of one pulse to Actuator 1 and one pulse to Actuator 2 has an average accuracy of 98.1% across all conditions (Fig. 7 A). One pulse to both actuators is an example of a reliable signal to use to stimulate the forearm for layered communication.

Additionally, the results show that it is possible to design haptic signals where certain signals contain layered information, such that part of a signal is easier to perceive and other elements of the signal are more difficult to understand without the additional information provided by the fingertips. For example, the maximum pulse of 1, 2, 3, or 4 could be encoded with more important messages that can be identified with high accuracy even in the forearm-only condition. The secondary signal, i.e. the second pulse and the locations of the pulses, could be less crucial for the participant to correctly interpret, but could provide more information to the participant. This secondary signal could then be understood with higher accuracy when the fingertips are involved. In summary, our results indicate that it is feasible to design haptic information so that urgent/important information is associated with signals that are detected with high probability, and less critical information is associated with more complex signals.

6) Precision Exceeds Accuracy for Some Signals: The precision for each signal is shown in Fig 7 A and the results demonstrate some nuances about how participants interpret the signals. For some signals, although the accuracy is low, the precision is quite high. For example, four pulses to Actuator 1 and three pulses to Actuator 2 results in 53.5% accuracy. However, that signal's precision is 86.7%. We observe that the precision for the signals where the pulses are the same continues to decrease as the number of pulses increases (one, one: 80.4%, two, two: 60.2%, three, three: 49.0% and four, four: 46.1%). As the number of pulses increases and signals become more difficult to perceive, participants may believe the stimulus is the signal with same number of pulses delivered to each actuator. Given that participants selected the maximum number of pulses with high accuracy, the results show that signals with the same maximum pulse number tend to be confused with other signals with the same maximum pulse number.

7) Potential for Tactile Masking: Exactly what mechanism causes participants to perform worse in the fingertips-and-forearm condition is not directly measured in this experiment. Work on tactile masking may provide some insights. Research shows that a vibration signal in one tactile channel (e.g. frequencies above 45Hz) that is applied to a location can mask, or decrease the perception of, another signal in the same tactile channel delivered to another location [37]. We can see from our results that amplitude is correlated with performance. Since masking would decrease the perceived amplitude of the vibration, tactile masking could explain our results. The data show that that participant accuracy is much lower when the signal amplitude is low (1.5g), but reaches a plateau as the amplitude gets higher, Fig. 4. Consequently, masking at high amplitudes may not have as large of an effect on accuracy as masking at low amplitudes. This could explain why the gaps between the accuracy of the fingertips-only and fingertips-and-forearm conditions grow smaller when the amplitudes of the signals increase.

8) Signal Design and IT_{est}: Overall, the IT_{est} values presented in Table IV indicate that there is higher information transfer in conditions where the fingertips are involved. However, given the limited number of trials taken during this experiment, the IT estimates are likely an overestimate of the true IT values [38]. The accuracy in the fingertips-only condition (3.54 bits) is comparable to other sets of vibration signals in the literature. Barralon *et al.* in a paper representative of findings on large sets of vibrotactile taps, reported an IT_{est} of 4 bits with 20 vibrotactile signals provided to the waist [23]. Although body-mounted dual-feedback devices could be

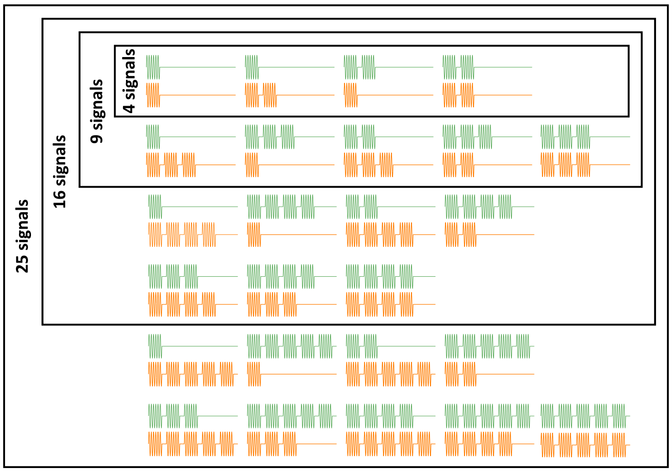

Fig. 8. The sets of 4, 9, 16, and 25 signals for Study 2. Orange signals are played on Actuator 1 and green signals are played on Actuator 2. Following the same notation as in Fig. 2 A, $f_s = 4$ Hz, $f_c = 150$ Hz, and t_f-$t_0 = 1250$ ms.

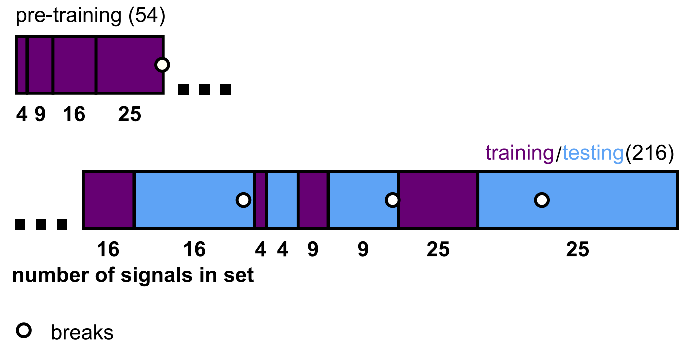

Fig. 9. The order and number of training and testing trials for one day. A training session is followed by the participant alternating between testing and training. During testing, this participant experienced S^{16}, followed by S^4, S^9, and S^{25}. This participant would follow this format for each day of experimentation but the order of S^4, S^9, S^{16}, and S^{25} and the trials within the testing sessions are randomized for each participant. Times where participants took breaks during the experiment are shown by black circles. Trials were randomized within each block section and across days.

created using many different feedback modalities, our results indicate that the vibration modality is a promising haptic stimulus. Using vibrotactile taps, we saw differences in participant performance across conditions. However, we did not directly measure what mechanisms allow participants to understand the cues, e.g. changes in intensity, counting, etc., so it would be worthwhile in future work to explore how participant performance changes with different signal sets.

V. Study 2: Number of Signals

We performed a second study to determine how participant performance changes with respect to the number of signals. By increasing the number of pulses, we also increased the difficulty of the task [29], allowing us to determine how task difficulty affects a body-mounted display. The results of this study provide guidelines for designing haptic feedback using our vibration signals and device architecture. This experiment investigates under what conditions the fingertips-only, fingertips-and-forearm, and forearm-only conditions have similar performance. Additionally, the study serves to quantify the information capacity of the tap vibration signals that we designed.

The study was conducted with 12 right-handed participants who all also participated in Study 1 (6 male and 6 female, aged 20-31). participants identified the taps with their fingertips-only, fingertips-and-forearm, and forearm-only, and with 4, 9, 16, and 25 total paired vibrotactile taps (Fig. 8). A constant amplitude of 6g was used for all conditions. The Stanford University Institutional Review Board approved the experimental protocol and all participants gave informed consent (Protocol #22514).

A. Methods

Data were collected from each participant over three days within a seven-day period. Each day, the participant received feedback to just one location, either fingertips-only, fingertips-and-forearm, or forearm-only. The location order was psuedo-randomized across participants so that each possible order permutation occurred twice. The signal sets were composed of 4, 9, 16, and 25 signals (Fig. 8). Each participant began with a pre-training period during which they experienced all signals in each signal set once (54 trials). During pre-training the signal set order was the same for each participant: 4, 9, 16, and then 25. The signals were randomized within each signal set. Following pre-training, the participant had a training session followed by a test session for each signal set (4, 9, 16, or 25 signals). This training/testing paradigm was used because of observations made during piloting that showed that, without extended training, participants continued to learn even during testing phases when there were differing number of signals.

The order of the 4, 9, 16, and 25 signals was determined by Latin squares and then psuedo-randomized along with location across participants. The order for the number of signals for a given participant was the same for the forearm-only, fingertips-and-forearm, and fingertips-only conditions. The participants were required to take a break 54 signals, regardless of whether they were in a testing or training phase.

A diagram of the experiment order for one condition is shown in Fig. 9. This diagram is the same for all locations, except that the order of the signals within each set is randomized. In the training session, each signal in the set was played one time in a random order. The testing set included three repetitions of each signal in the signal set in a random order.

To further to mitigate observed learning effects, we only recruited participants who had participated in Study 1, because they had experience with the signals, and we anticipated that learning effects would be reduced in that population. We collected data for 270 trials per location and 810 experimental trials per participant. With 12 participants this resulted in a total of 9720 trials (3888 training trials and 5832 test trials). The participants and actuators were positioned as described in Section III-B. The participants completed a post-study questionnaire in which they are asked to compare the difficulty of the four signal sets.

TABLE V
PAIRWISE COMPARISONS OF LOCATIONS, GIVEN ON THE RESPONSE SCALE AND USING THE TUKEY METHOD. P-VALUES FOR STATISTICALLY SIGNIFICANT PAIRS ARE SHADED IN GRAY

Number of Signals					
contrast	**ratio**	**SE**	**low CI**	**high CI**	**p-value**
finger, arm	0.28	0.0341	0.21	0.37	<.0001
finger, finger/arm	0.79	0.1060	0.57	1.08	0.18
arm, finger/arm	2.85	0.3171	2.20	3.70	<.0001

TABLE VI
PAIRWISE COMPARISONS OF THE NUMBER OF SIGNALS, GIVEN ON THE RESPONSE SCALE AND USING THE TUKEY METHOD. P-VALUES FOR STATISTICALLY SIGNIFICANT PAIRS ARE SHADED IN GRAY

Number of Signals					
contrast	**ratio**	**SE**	**low CI**	**high CI**	**p-value**
4 sig, 9 sig	0.75	0.14	0.47	1.21	0.43
4 sig, 16 sig	0.48	0.082	0.31	0.74	0.0001
4 sig, 25 sig	0.35	0.057	0.23	0.53	<.0001
9 sig, 16 sig	0.63	0.073	0.47	0.85	0.0004
9 sig, 25 sig	0.46	0.049	0.35	0.60	<.0001
16 sig, 25 sig	0.72	0.057	0.59	0.89	0.0002

B. Data Analysis

As in the previous experiment, for a given trial, the participant was either correct or incorrect. Due to the binomial nature of the data, we fit a general linear mixed-effects model assuming a binomial distribution and a logit link function. We created a three-level factor for location (H_{loc}), a four-level factor for the number of signals (H_{sig}), and a multi-level factor for their interaction term ($H_{loc:sig}$). A twelve-level variable for participant, $H_{participant}$, is also used to account for random effects. For each factor we fit a coefficient, β, The model took the following form:

$$D_v = \beta_{loc} H_{loc} + \beta_{sig} H_{sig} + \beta_{loc:sig} H_{loc:sig} + (1|H_{participant}) \quad (3)$$

C. Results

Both location ($\chi^2(2) = 276.04,\ Pr(>\chi^2) < $ 2e-16) and the number of signals ($\chi^2(3) = 85.78,\ Pr(>\chi^2) = <$ 2e-14) were significant factors. Their interaction was not significant ($\chi^2(6) = 9.49,\ Pr(>\chi^2) = 0.15$). Posthoc testing, reported in Tables V and VI, showed which locations and number of signals were statistically significantly different. The average accuracy for all conditions is summarized in Fig. 10. The IT_{est} was computed for each participant and the average values for all participants across all conditions are shown in Fig. 11. The precision and standard error for 4, 9, 16, 25 signals were 0.90 ± 0.03, 0.88 ± 0.04, 0.84 ± 0.04, 0.81 ± 0.04, respectively.

D. Discussion

We demonstrate that changing the number of signals affects average participant performance – as the number of signals increases, participant accuracy decreases (Fig. 10). However, the information transfer continues to increase with the number of signals increase despite decreased accuracy (Fig. 11), indicating that more signals can be added and still transfer more information. The continued decrease in accuracy (Fig. 10) indicates that it is possible that there exists a number of signals where the amount of information transferred does not continue to increase. The curve indicates that the channel capacity (the maximum number of levels that can be communicated) for our signal set is likely between 3.5 and 4 bits. The accuracy, as seen in Fig. 10, shows a downward trend as the number of signals increases for the fingertips-only and fingertips-and-forearm conditions. The forearm shows the same trend, but the interpretability of the results is obscured between 16 and

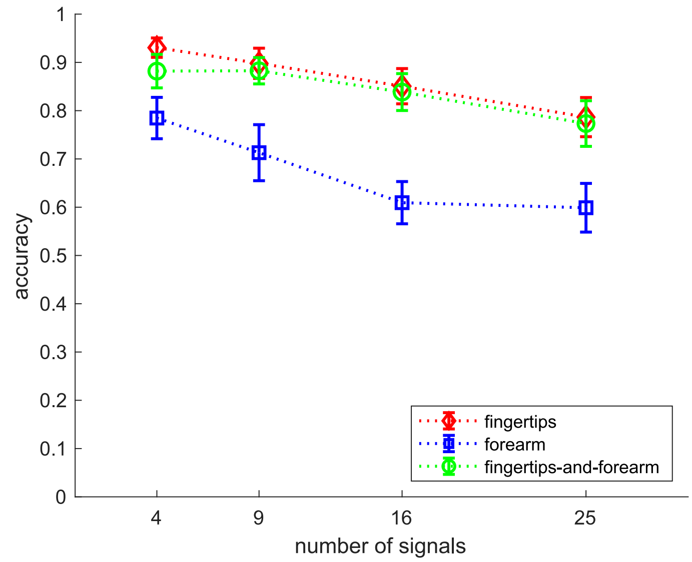

Fig. 10. The accuracy for each number of possible signals in the set (4, 9, 16, and 25). The accuracy has a decreasing slope in all conditions as the number of signals increases. The error bars represent the standard error.

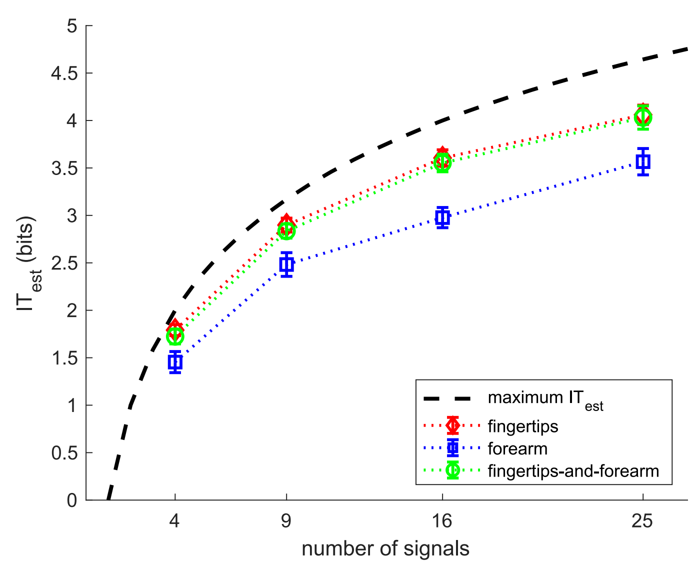

Fig. 11. The IT estimate (IT_{est}) for each condition and for each number of possible signals. In all conditions, the IT_{est} increases as the number of signals increases. The error bars represent the standard error.

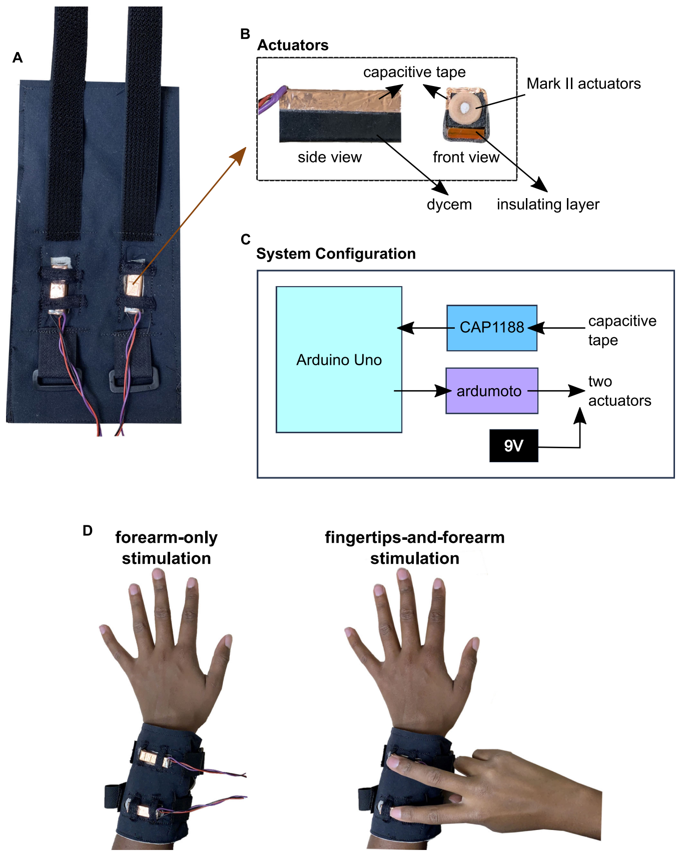

Fig. 12. (A) Actuators are affixed to the arm using an adjustable wearable fabric sleeve. The actuators are secured using elastic fabric bands that apply normal force but do not prevent actuator vibration in the lateral direction. (B) The device is composed of two Mark II voice coil Haptuators, which are covered on one side by a layer of capacitive tape to measure finger contact, and on the other side by an acrylic insulating layer and a layer of Dycem. The acrylic layer is used to prevent false positives caused by conduction through the voice coil to the conductive tape, and the Dycem is used as a high-friction interface material so that the actuators make secure contact with the skin. (C) System configuration for all hardware components. The capacitive inputs are read by a CAP1188 board and ported to the Arduino Uno. The device inputs and outputs are read and controlled by an Arduino Uno, and the voice coil actuators are powered by a 9V battery and an ardumoto, a dual motor driver based on the L298 Hbridge. (D) The two configurations in which the device can be used.

25 signals. This result could indicate that the accuracy will approach a plateau for the fingertips-only and/or fingertips-and-forearm conditions as the number of signals increases. Alternatively, the result could indicate that the accuracy only approaches a plateau for the forearm.

With a signal set of 4 signals, a total overall accuracy of 93% and 88% is achieved in the fingertips-only and fingertips-and-forearm condition, respectively. These results show that the vibration signals can achieve similar accuracy to other devices that are able to deliver cues with high accuracy [17], [39]. It is possible that there exist signal sets with higher precision for which signals are more differentiable.

These results confirm that participants have higher accuracy in all conditions with signal sets containing fewer signals. However, if sending large amounts of data is prioritized, we have to accept that participant accuracy will decrease. The accuracy of the forearm-only condition is lower than the accuracy of both the forearm-and-fingertips condition and the fingertips-only condition for all numbers of signals. Although there was no significant interaction effect between location and number of signals, we observe that, with fewer signals, the accuracy of the forearm-only condition (78% with 4 signals) begins to approach the accuracy of the fingertips-and-forearm (88% with 4 signals) and fingertips-only conditions (93% with 4 signals). This result shows that when designing a body-mounted wearable device, the size of the signal sets delivered to the forearm can be limited, and a larger set of signals to the fingertips-and-forearm can be delivered, such that participant accuracy and the amount of encoded information are balanced. As in Study 1 (Section IV), it is possible that the forearm-only condition could be improved by moving the actuators farther apart or increasing the stimulus onset asynchrony [33], [35], [40]. We also demonstrate that participant performance at 6g in the fingertips-and-forearm and fingertips-only conditions is not statistically significantly different as the number of signals changes, confirming the result from the study in Section IV. Investigating the effects of amplitude on accuracy with different numbers of signals would help answer the question of whether the effects of body-mounting the device are exacerbated, minimized, or remain the same as the number of signals changes. It is possible that as the task becomes easier (e.g. there are fewer signals), the difference between the fingertips-and-forearm and fingertips-only conditions becomes insignificant, just as the difference between the forearm-only and fingertips-only conditions became smaller with smaller numbers of signals.

VI. Conclusions

In this paper, we tested and demonstrated a device architecture that provides both a body-mounted display for the forearm and a display that can be explored by the fingertips. This dual-function device not only leaves the hands free, but also permits haptic designers to exploit available skin real estate at other locations on the body.

We showed that using a body-mounted tactile display that transfers information to the fingertips and the forearm simultaneously has inferior participant accuracy than using the fingertips exclusively, unless vibration amplitude is accounted for. We also provided insights into participant performance when simultaneous vibration signals are sent to multiple locations. For example, the maximum pulse was identified by participants with very high accuracy (99% in all conditions at 6g), even when the paired signal was not correctly identified. Additionally, including the fingertips (i.e., the fingertips-and-forearm condition) reduced spatial confusion introduced in the forearm-only condition; there was no statistically significant difference in the number of flipped signals between the fingertips-only and fingertips-and-forearm conditions.

We also showed how participant accuracy changes with the number of signals and demonstrated that reducing complexity, or reducing the number of signals, has a measured positive effect on participant accuracy. This indicates how we could use our device architecture to effectively communicate information and achieve the highest participant performance with this set of signals.

In ongoing work, we are investigating how a wearable system can be used beyond a laboratory environment. We developed a wearable prototype that allowed us to explore interesting areas of future work (Fig. 12). We implemented an example communication strategy using the wearable prototype, where the signals sent to the user were the paired vibrotactile taps discussed in Section III. First, the user receives a signal to the forearm; then when the user chooses to, they touch the actuators; when the actuators are touched, the device replays the same signal. The prototype and communication strategy were used in several haptics educational demonstrations with users of different ages and backgrounds. Anecdotally, during these demonstrations, the device performed robustly, and the users could observe the differing roles of forearm and fingertips-and-forearm stimulation (for alerts and detailed communication respectively), due to differing vibrotactile sensitivity at different locations.

The current device and example communication strategy serve as building blocks for imagining additional application scenarios. For example, the portable device can be used for:

- Receiving large or small sets of discrete encoded messages. The device paradigm allows users to revisit messages initially received on the forearm with their more sensitive fingertips.
- Communicating language by encoding the vibrations into letters, consonants or specific words, as previously demonstrated in [41] and [42]. Using our device, one could design a communication strategy that uses both the fingertips and forearm together and separately.
- Creating a bidirectional communication interface. Users could send or record vibration signals by tapping on the capacitive sensors already embedded in the actuators, and also receive signals to the fingertips and/or forearm. This could be used for human-human interaction or for human-machine interactions.
- Exploring how human movement, distractions, and active touch affect performance.

The results of this work emphasize the potential to design haptic devices for the fingertips that are mounted on the body, and reveal ways the displays can be made more effective. Additional future research will consider a wearable and portable display, other haptic modalities, and different haptic feedback to different locations on the body. We will also explore whether increasing the amplitude and decreasing the number of signals have an additive positive effect. Finally, we aim to understand exactly what fundamental mechanisms cause participant accuracy to decrease when feedback is delivered simultaneously to both the fingertips and forearm compared to the fingertips alone.

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