Short Paper

Evaluating the Effect of Stimulus Duration on Vibrotactile Cue Localizability With a Tactile Sleeve

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***Abstract*—Vibrotactile arrays are appealing as wearable haptic devices, since designers can vary parameters including cue location and duration to create distinct haptic icons to represent a wide range of information. Vibrotactile sleeves have typically used cues that vary in duration from 100 to 400 ms, but it is not well understood how cue duration might affect localizability of stimuli. Using an experimental protocol typically employed to understand how our visual system can localize stimuli, we examined localization of tactile cues for tactors spaced at fixed locations along the forearm while we varied cue duration between 100 and 400 ms. To validate our experimental methods and hardware, we also evaluated visual cue localization performance. Our visual cue localization results were in agreement with prior experiments showing that varying noise in visual cues affects cue localization. More importantly, this experimental paradigm allowed us to verify that participants could successfully localize tactile cues regardless of duration. Response variance in tactile localizability was much greater than the visual case. There was also an effect of stimulus location on tactile localization performance. Our findings support the variation of tactile cue duration in the 100 to 400 ms range for tactile arrays positioned on the forearm.**

Index Terms—tactile perception, wearable haptics, tactile array, haptic localization.

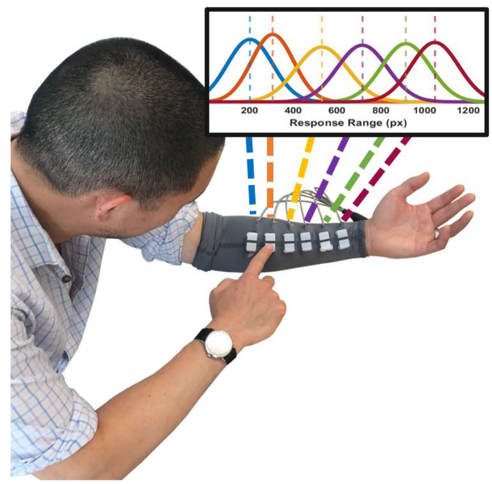

Fig. 1. We examine the ability of users to localize cues generated by vibrotactile actuators embedded in a sleeve at fixed intervals along the forearm. We explore how cue duration affects the variance in localizability. During experiments, the tactors were occluded from view so that tactile localizability could be evaluated without reliance on visual feedback.

I. Introduction

Wearable haptic displays are becoming increasingly advanced in the number and types of cues that can be conveyed to the user, enabling these devices to be used to transmit complex information to the wearer. Devices feature vibrotactile arrays [1], [2], skin stretch mechanisms [3]–[5], and squeezing bands [6]. In some cases, multiple types of stimuli can be conveyed with the same device [7]–[9]. Vibrotactile arrays are particularly attractive as wearable haptic devices, since low-profile vibrotactors can be incorporated into fabric to create sleeves [1] or vests [2] that are easily donned and doffed. Arrays of vibrotactors are capable of encoding large cue sets since cues can be designed to incorporate varying numbers of tactors, and one can even create vibrotactile "gestures" by varying the sequencing of the vibrations across tactors [1]. Reliable perception of the vibrotactile cues is important.

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While some vibrotactile devices are used to convey sensory information that is typically experienced through the sense of touch, such as in prosthetics applications [10], [11], some instances of wearable haptic systems use vibrotactile feedback to convey information that is typically transmitted visually or aurally. For example, vibrotactile feedback has been used to guide arm movements [12], to convey cursor movement smoothness for surgical training [13], and to encode phonemes as a means to transmit words to the user [1]. In these instances, the user must learn these associations. This process, called cross-modal associative learning, depends on both the ability of the user to learn the mapping of information from one modality to the other [14], and their ability to reliably perceive the haptic cues themselves [15]. To take full advantage of the potential to communicate complex information with vibrotactile arrays, it is important to quantify human perceptual performance associated with these cues.

Given the increasing use of arrays of vibrotactors for the transmission of complex information, we seek to quantify the degree to which vibrotactile cues can be localized by a user when cues are displayed individually to the forearm at fixed locations within a sleeve-type array (see Fig. 1 for a conceptual representation of this task). Localizing a tactile cue is the ability to spatially locate a stimulus presented in a sensory modality [16] and differs from two-point discrimination tasks by capturing the ability to localize a series of stimuli presented at some fixed spacing along a surface of the skin, rather than varying distance between two distinct cues to determine the distance at which the cues are perceived as distinct [17].

Several of the most recent haptic displays are tactile arrays worn as sleeves [1], [18], [19] given the attractiveness of clothing-like form factors for wearable devices. Despite this fairly wide adoption of vibrotactile displays for the forearm, individuals are reportedly poor at localizing vibration cues presented to this part of the body when asked to respond via categorical or discrete response options [16], [20], [21]. For example, Wong *et al.* evaluated localization and information transfer of five tactors embedded in a tactile sleeve along the dorsal side of the forearm and reported that participants were able to identify only 2-3 of the five tactors reliably [18]. Since the reliable transmission of complex information encoded as haptic cues requires the user to both correctly perceive the cue and recall the cross-modal associative map, it is important to study tactile cue localizability to determine how stimulus parameters (e.g. frequency, amplitude, or duration) selected for wearable vibrotactile displays may affect performance.

Prior research has explored, to some extent, how vibrotactile cue characteristics can affect localizability of tactile stimuli. Cholewiak *et al.* studied the effects of stimulus frequency on localizability of tactile cues for cues driven at 100 and 250 Hz, but they did not report any significant results for this range [16]. Zhao *et al.* also examined cues with different frequencies, and also varied cue duration, location, and spatial patterns [22]. They reported a small but significant difference in recognition rates for vibrations presented on the dorsal side of the forearm at two frequencies (30 Hz and 250 Hz), with performance being slightly better for higher frequency cues [22]. Although it is possible that localization may be affected by frequencies outside this range, many commercially available tactors are designed to operate at a given amplitude and frequency dictated by the mechanical resonance of the actuator itself [23]. This limits the tunability of frequency and amplitude characteristics of vibrotactile cues, making it potentially less impactful to consider how frequency or amplitude affects localizability of cues. Further, low amplitude stimuli are easily masked by successive stimuli [22].

In contrast, cue *duration* is often varied in tactile stimuli, particularly in tactile communication devices. For example, duration of vibrotactile cues is typically varied to provide "short" or "long" pulse lengths or cues that range between 100 and 400ms [1], [8], [22]. Zhao *et al.* reported a small but significant difference in recognition rates for vibrations presented on the dorsal side of the forearm at two different durations (150 ms and 400 ms), with performance being slightly better for longer duration cues [22]. Still, it is not well understood how this duration range (100-400 ms) may affect the localizability of cues within a tactile array. If this parameter influences localizability, then selecting cue durations that result in improved localizability could be one method of improving the effectiveness of these complex haptic systems.

In this paper, we quantify the effect of tactile cue duration on the localizability of vibrotactile cues using a wearable, six-tactor array worn on the forearm. Localization of tactile cues has typically been assessed with discrete choice tasks [16], [18]. In these experiments, one tactor within an array is actuated, and participants are asked to identify which tactor location was active. In contrast, we are interested in the ability of participants to localize tactile cues along a *continuous* response spectrum. To do so, we adapt standardized experimental methods used to evaluate localization performance in the visual sensory modality to the tactile domain. In this methodology, subjects indicate the perceived center of a cloud of visual stimuli presented on a screen, either via mouse click or touchscreen input, while the noise level of the visual stimuli is varied [24]–[26]. The noise level is set in Gaussian dot clusters (or dot clouds) presented as the visual stimuli, and this manipulation proportionally modulates the subject response variance to the visual cues. This methodology will allow us to explore how localization performance varies when different aspects of the tactile cues are modulated (for example, as we do in this paper, by varying cue duration).

II. Experimental Method

We assess the localizability of cues in both the haptic and visual modalities, along a continuous spectrum along the forearm or across the screen. We implement an experimental protocol to evaluate effect of cue duration on tactile cue localizability. Here, our objective is to determine if tactile cue duration, an easily tunable parameter in the design of tactile cues, will affect tactile cue localization performance using our wearable six-tactor array. We also validate our experimental hardware and protocol by confirming the effect of noise in visual stimuli on visual cue localizability via a touchscreen.

A. Participants

A total of 16 participants took part in this study (11 female, 14 right-handed, 20–29 years old, average age 24). All participants were healthy adults and did not report any cognitive or sensory impairments that would inhibit their ability to complete the experimental tasks. All participants gave informed consent, and the protocol was approved by the Rice University Institutional Review Board (IRB-FY2021-29).

B. Experimental Hardware

A custom designed Vibro-Tactile Sleeve (VT-Sleeve) (Fig. 2) was used as the wearable tactile array. Six vibrotactors (2.5VAC, 10 mm Linear Resonant Actuator; Jinlong Machinery & Electronics, Inc.; Part no. G1040003D) were embedded in a compression sleeve (Under Armour) via custom 3D-printed housings (VisiJet M2R-CL material). Vibrotactors were press-fit into the housing that clipped into slits cut along the sleeve, spaced 30 mm apart, which satisfies the two-point discrimination threshold reported for successive touch stimuli [27]. Each tactor housing was secured with Velcro strips and Flat Ribbon Cable (CNC Tech; Product no. 304-28-20-MC-0100F) connecting the tactors to a custom amplifier.

C. Tactile Stimuli

Tactile cues were envelope sine waves at the tactors' optimal driving frequency (175 Hz) and nominal voltage (2.5 Vrms). This resulted in cues that varied in amplitude from -0.72 to 0.63 Grms, measured for a tactor mounted on a block of ABS using the methods described by Pezent *et al.* [28]. Cues were presented at three duration conditions: 100 (DUR1), 200 (DUR2) or 400 ms (DUR3). Tactile cues were rendered via Syntacts with a digital-to-analog converter (ASUS; Xonar U7 MKII 7.1 USB), and signals were amplified with a Syntacts amplifier [28]. Cues were presented along the volar side of the left arm at one of the six tactor locations, referred to as T1 through T6 (Fig. 2).

D. Visual Stimuli

Visual cues were clouds of 20 black dots (diameter 16 px; visual angle = 0.44° when centered) and were presented at three noise conditions: high reliability (HR), medium reliability (MR), and low reliability (LR). The dot locations of each cloud presented (i.e., distance in px from each dot to the center of the cue) were sampled from bivariate Gaussians at one of three standard deviations. For HR, the vertical and horizontal standard deviations were set to 36 px (visual angle = 0.98° when centered). For MR, standard deviations were set to 146.5 px (visual angle = 4° when centered). For LR, standard deviations were 256.5 px (visual angle = 7° when centered).

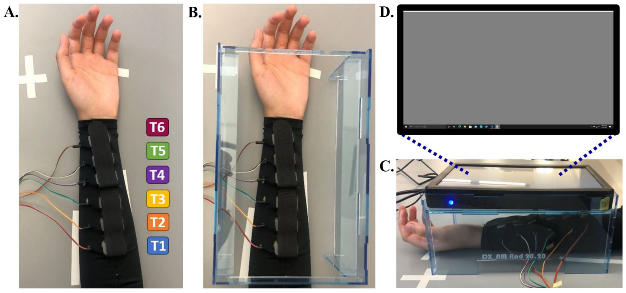

Fig. 2. VT-Sleeve used in experiments. A. The VT-Sleeve was worn on the left arm with tactors labeled T1 to T6; tactors were placed on the volar side of the arm. B. Top view of subject's arm under the acrylic box used for calibrating the fit of the sleeve to ensure consistent tactor placement and spacing. C. Side view of setup showing touchscreen display positioned on top of the box, occluding the array from subject's view. D. Screen shot of response display. The screen remained grey, with no landmarks for tactor location or outline of the arm, throughout tactile cue presentation and prior to the subject response. The screen flashed after the subject's response was recorded. The response screen was the same for the visual task.

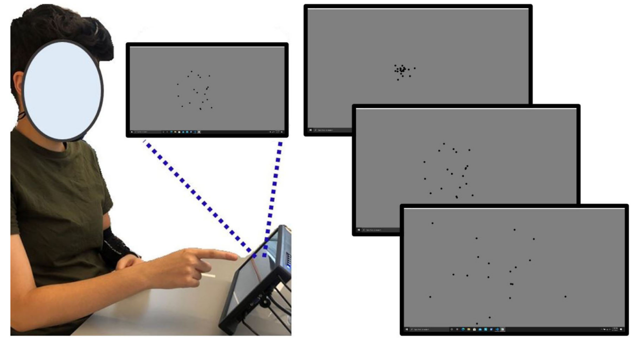

Fig. 3. Touchscreen set-up and display for visual task. (left) Subject responds via touchscreen when presented with a visual cue. (right) Screenshots of display when visual cues are presented at location V3 for each noise level (back to front: HR, MR and LR).

Visual cues were presented along the lateral dimension of a screen at one of six locations, with the center of each cue spaced 274 px apart. All cues were presented at the same vertical location, with the clouds appearing at the middle of the screen in the vertical dimension. The six visual locations are referred to as V1 (left side) through V6 (right side). The set-up and cues are depicted in Fig. 3.

E. Experimental Task and Setup

The experimental task was to localize cues presented along the arm or across a screen. Tactile or visual cues were presented randomly at one of the six locations, and participants were instructed to respond to where they perceived the center of each cue to be by pointing to a location on a touchscreen as accurately as possible. Participants wore noise cancelling headphones that played pink noise.

A touchscreen (Elecrow, Model: SFT101 T) was used to capture participant responses to both tactile and visual cues along a continuous spectrum. The active area to which subjects could respond was 1920×1031 pixels (px) (238 mm $\times$ 128 mm) and colored grey. Responses were recorded along the active area of the touchscreen (in px). For tactile conditions, the touchscreen was positioned over the participant's left arm with a custom-built, laser-cut box (Fig. 2). For visual conditions, the screen was set directly in front of the participant, in an upright position (Fig. 3).

To configure participants for the visual localization task, the experimenter measured 260 mm along the desk from the participant's vantage point (directly under their nose) to a point on the desk in front of them, where a stand to hold the touchscreen in an upright position was placed. Participants wore the VT-Sleeve on their left arm for the entirety of the experiment (see Fig. 2). The bottom edge of the sleeve was aligned with the boundary between the wrist and palm. Prior to the start of the experiment, the tactor locations on each participant's arm were calibrated using the box, such that T1 and T6 were consistently aligned under the touchscreen for all participants. The arm was held as flat as possible on its dorsal side for tactile conditions and occluded from view by the touchscreen, as shown in Fig. 2 C. Participants could hold their arm in any position during the visual task.

F. Procedure

The experiment was performed in a single session comprised of three blocks of 360 trials each and lasted no more than 90 minutes. Each block tested one condition each of the tactile and visual modalities: [DUR1 & HR], [DUR2 & MR], [DUR3 & LR], which were presented into four alternating runs (e.g. Block 1: DUR1, HR, DUR1, HR). The order of presentation of each block was randomized across participants. Participants were given a 1-2 minute break between each run and a 5 minute break between blocks.

Each run included 90 randomly ordered stimulus presentations (15 repetitions at each of the six stimulus locations, for a total of 30 presentations in each block). Depending on the tactile condition, stimuli were presented for 100, 200 or 400 ms. All visual cues were presented for 100 ms, but varied in their noise conditions (HR, MR, and LR). After a cue was presented, subjects had an unlimited amount of time to respond to where they perceived the stimulus to be by touching a location on the touchscreen.

For both the tactile and visual tasks, subjects responded by touching the tip of their right index finger to a blank grey response screen (see Fig. 2 D). The response screen was the same for both the tactile and visual tasks. As such, no landmarks indicating tactor location or outline of the arm were provided during the tactile runs. A "mouse capture" function in C++ was used to record the location on the screen touched by the participants. This function returns the x and y location for a single pixel for the touch response. After the subject responded, the screen flashed to indicate that the response was recorded. Participants were not given the opportunity to adjust or redo their response before proceeding to the next trial. An inter-stimulus interval of 1500 ms was used to fill the time after the participant's response to the onset of the next stimulus cue.

G. Data Analysis

The lateral pixel values of responses were considered for analysis for both tactile and visual conditions. We computed the mean response location and variance for each participant across modality (tactile and visual), stimulation location (1 through 6), and condition (noise or duration level). Response means and response distributions (capturing the variance) for an example participant can be seen in Fig. 4 A for the tactile localization conditions and Fig. 5 A for the visual conditions.

We conducted a two-way repeated measures ANOVA to determine the effect of stimulus location and condition on localizability. This analysis was carried out for both dependent variables, the response mean (px) and the response variance (px^2). We also examined interactions between stimulus location and condition. Finally, in the case of a significant main effect, we completed post hoc tests.

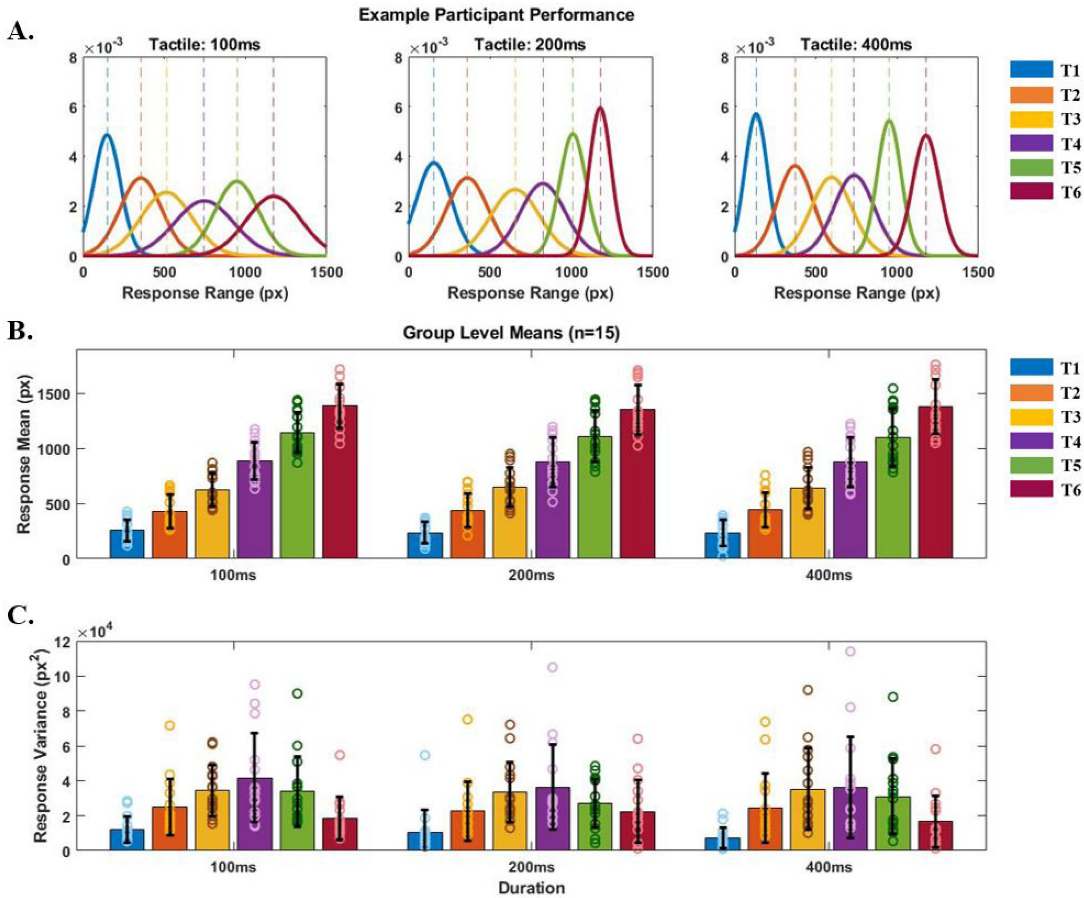

Fig. 4. Vibrotactile stimuli localization results. A. Example response distributions showing normal Gaussian distributions fit to a representative subject's responses to each of the six tactile cues, for each condition. B. Mean response to each stimulus cue. C. Response variance to each cue.

One subject, whose mean variance was more than 2.5IQR from the group mean in more than 25% of visual stimuli conditions, was removed from subsequent analysis. Results are reported for the remaining 15 participants.

III. Results

A. Tactile Localization Performance

Our primary outcome measure was the mean pixel location associated with each stimulus. Response means for each tactile condition at the group level are shown in Fig. 4B. There was a main effect of stimulus location ($F(5252) = 230.79$, $p < 0.0001$), but not of duration ($F(2252) = 0.098$, $p = 0.907$). Tukey's Honestly Significant Difference Procedure was completed on the group means to determine localizability of each tactor location. All group means were significantly different from one another for all comparisons ($p < 0.0001$), suggesting that subjects were able to successfully localize tactors along the forearm. There was no significant interaction effect of stimulus location and duration on the response means ($F(10, 252) = 0.086$, $p = 0.999$).

We also examined the effect of stimulus location and duration on the variance in localizability. Response variance for each tactile condition at the group level is shown in Fig. 4C. There was a significant main effect of stimulus location ($F(5252) = 14.636$, $p < 0.0001$), but not of duration ($F(2252) = 0.489$, $p = 0.614$). Tukey's post hoc analysis showed pairwise differences in response variance between many of the tactors (T1 was significantly different than T2, T3, T4, and T5; T2 was significantly different than T1 and T4; T3 was significantly different than T1 and T6; T4 was significantly different than T1, T2 and T6; and T5 was significantly different than T1 and T6, and T6 was significantly different from T3, T4, and T5). All were significant at the $p < 0.01$ level except T5 vs. T6, which was significant at the $p < 0.05$ level. There was no statistically significant interaction effect of stimulus location and duration on the response variance ($F(10, 252) = 0.240$, $p = 0.992$).

B. Visual Localization Performance

Response means for each visual condition at the group level are shown in Fig. 5B. There was a statistically significant interaction between the effects of stimulus location and noise level on the response means ($F(10, 252) = 18.287$, $p < 0.0001$). Therefore, to confirm that visual cues were localizable at each noise condition, a one-way ANOVA was run to determine the effect of stimulus location on response means. Simple main effects of stimulus location on response means were reported at each visual noise condition (HR: $F(5, 84) = 7.515e + 03$, $p < 0.0001$; MR: $F(5, 84) = 3.339e + 03$, $p < 0.0001$; LR: $F(5, 84) = 1.845e + 03$, $p < 0.0001$). For each visual condition, Tukey's Honestly Significant Difference Procedure was completed on the group means to determine localizability of the visual cues. All group means were significantly different from one another at each noise level ($p < 0.0001$). This finding confirms the localizability of the visual cues, at each noise level, as expected.

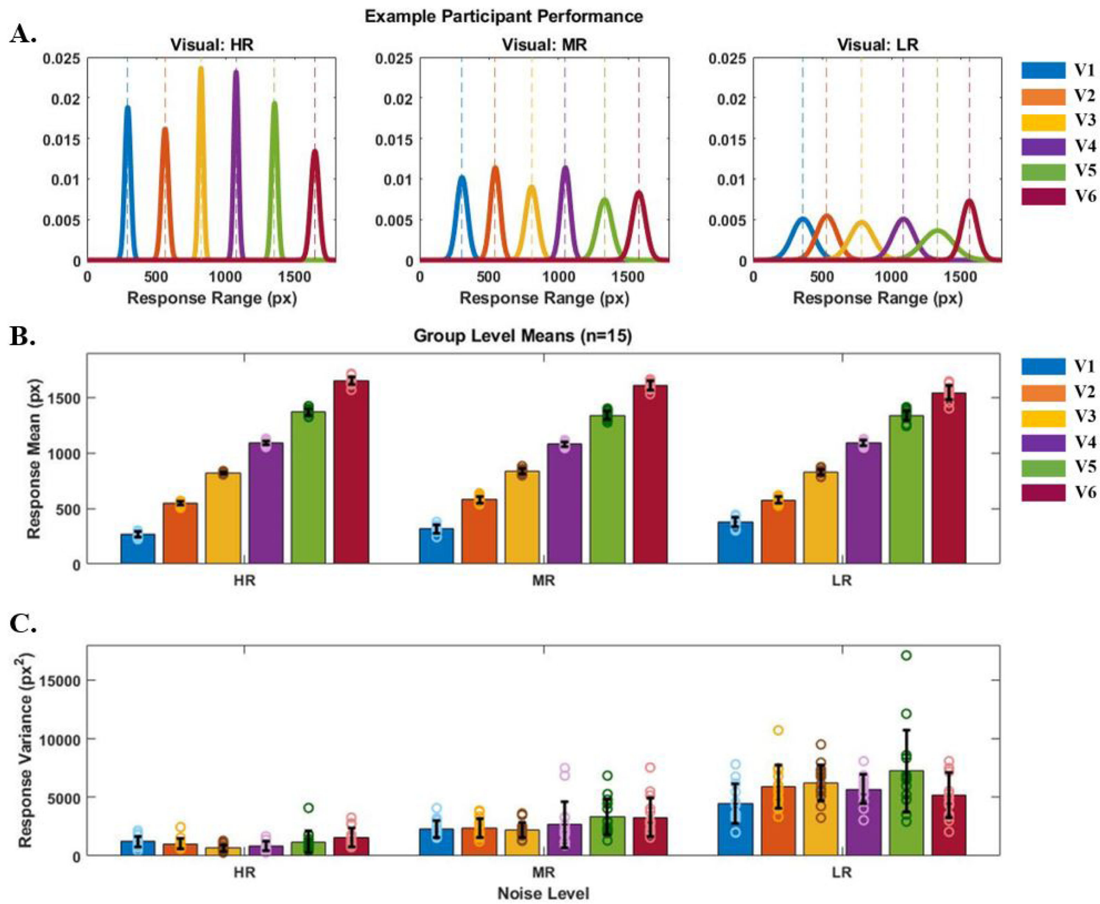

Fig. 5. Visual stimuli localization results. A. Example response distributions showing normal Gaussian distributions fit to a representative subject's responses to each of the six tactile cues, for each condition. B. Mean response to each stimulus cue. C. Response variance to each cue.

Response variance for each visual condition at the group level is shown in Fig. 5C. There was a statistically significant interaction effect between stimulus location and noise level on the response variance ($F(10, 252) = 2.472$, $p < 0.01$). Therefore, to confirm the effect of stimuli location on variance, a one-way ANOVA was run. There was a significant effect of stimulus location on response variance at each cue location for the HR ($F(5, 84) = 4.138$, $p < 0.05$) and LR noise levels ($F(5, 84) = 3.075$, $p < 0.05$). For the HR condition, Tukey's post-hoc analysis showed that only the response variance to V6 was significantly different from V3 ($p < 0.01$) and V4 ($p < 0.05$). For the LR condition, Tukey's post-hoc analysis showed that only the response variance to V1 was significantly different from V5 ($p < 0.01$).

IV. Discussion

We studied localizability of vibrotactile stimuli presented with a 6-tactor array worn on the forearm. Vibrotactile cues were considered to be "localizable" if the response means to each of the six cue locations were determined to be significantly different to the response means of every other cue location. Since there was a main effect of tactor location on the response means, we conducted post hoc analyses and determined that each response mean was significantly different from every other response mean, indicating that the vibrotactile cues were localizable along the forearm.

We then investigated the effect of vibrotactile cue duration, presented at three levels (100, 200, and 400 ms), on localizability. Results showed that duration had no statistically significant effect on localization. There was no main effect of duration on the response mean or response variance to tactile cues presented along the sleeve. This finding is encouraging for tactile displays that use cues that vary in duration between 100 to 400 ms [1], [8], since our findings suggest that localizability of cues should not vary based on duration. The effect of duration on localizability of tactile cues in wearables was previously reported by Zhao *et al.* [22], who found that localization performance was better for longer (400 ms) versus shorter (150 ms) duration cues. Their task involved discrete rather than continuous responses from participants. Another contribution of this paper is a validated experimental hardware implementation and protocol that can be used to evaluate tactile cue localization with a continuous response variable. While other groups have implemented experimental protocols that allow for continuous response variables when identifying tactile stimulus locations (e.g. via a mouse cursor or touchscreen [29], [30]), no prior studies have used this methodology to study tactile cue characteristics on cue localization performance. Rather, these groups have studied the interactions between visual and haptic stimuli that may be in agreement or in conflict for cue localization tasks.

We only considered cue durations that are typically used in wearable tactile arrays (100-400 ms), and showed that this manipulation did not affect localizability. Future work might explore cue durations that are shorter or longer than this range. The localization of auditory cues is known to improve with longer duration stimuli, for example [31], [32], but it is also known that the absolute threshold of tactile perception is influenced by cue duration, among other factors [23].

It is notable that the variance across tactor *locations* was not consistent. Variance in the localization of tactile cues near the extents of the sleeve, at the wrist and elbow, was much lower than variance of cues presented towards the middle of the forearm. This is consistent with prior research that has shown that tactile localizability is superior at natural anatomical locations near joints, such as the wrist, elbow, and shoulder [16]. While Chen *et al.* observed better localizability performance for vibrotactile cues presented at the wrist than at the elbow [33], in our study, the localizability at these two locations was not significantly different (Fig. 4). The tactile array presented by Tan *et al.* used cues targeted to different regions of the forearm [1]. To overcome the differential perception of tactile stimuli at different locations on the arm, they used a calibration method to ensure that stimulus intensities were perceived as equal regardless of location [34]. Our findings support such an approach when using vibrotactile arrays that span the length of the forearm.

To validate our experimental methods, we included trials that required participants to localize visual cues that varied in noise level using the same touchscreen interface for entering their responses. Our visual cues were presented at one of three noise levels, an experimental manipulation that is known to affect the variance of localizability of the visual stimuli [24]–[26]. Our results confirm that participants can successfully localize visual stimuli presented at six locations, regardless of noise level, using our touchscreen input device. When noise level in visual cues is low, we observe very low response variance, and the variance increases proportionally with increasingly noisy stimuli.

It is important to note that, unlike the tactile case, the response variance was relatively consistent across all visual stimuli locations, and response variance increased as noise levels increased. These findings suggest that our ability to localize visual stimuli is independent of stimulus location, so long as the stimuli are within the participant's field of view and have the same noise characteristics. The inclusion of both visual and tactile localization tasks allows us to compare mean and variance of cue localization across these two sensory modalities, where we observe much lower variance for visual cue localization than for tactile cue localization for the range of stimuli tested here. This provides some insight into our tactile localizability results. In the visual case, the manipulation of noise in the stimulus has a clear effect on response variance. In the tactile case, the manipulation of duration had no such effect, and we observe that the variance in responses in the tactile case is much greater in magnitude than the visual case. This is not surprising, given our knowledge of the poor localizability performance for tactile stimuli, especially those presented on the forearm, where the density of mechanoreceptors is low [20], [21], [23]. Our participants are able to localize cues with a robust sensory system (visual), but do not achieve the same performance when relying on a noisy sensory system (tactile).

Our results expose challenges for designers of wearable tactile arrays that are intended for transmitting complex information. Tactile stimulus duration modulation between 100 and 400 ms did not have an effect on localizability, but it is possible that durations outside of this range, or other manipulations of the tactile cues themselves might improve performance. Indeed, prior work has explored manipulations of cue frequency, stimulus location, and the use of dynamic temporal patterns to create illusory movements [16], [22]. Other groups have employed calibration procedures to vary stimulus intensity at different tactor locations to ensure that they were perceived as equally intense by the wearer [34]. There may be other approaches that could be used to improve the localizability of tactile cues in the middle of the forearm.

V. Conclusion

Vibrotactile arrays embedded into wearable sleeves can be configured to transmit cues that encode complex information. Successful implementation of such systems requires the user to both correctly perceive the tactile cues and to recall the mapping of encoded information to a particular cue. We examined localization of six tactile cues spaced along the forearm, and manipulated cue duration to determine if duration of stimuli had an effect on localizability. We determined that participants can successfully localize the tactile cues, but duration did not have a statistically significant effect on performance. Compared to visual stimuli localizability, response variance in tactile localizability was much greater, and unlike in the visual case, there was an effect of tactor location on performance. Our findings support the variation of tactile cue duration in the 100 to 400 ms range for tactile arrays embedded in sleeves worn on the forearm.

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