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Effects of Stimulus Frequency and Location on Vibrotactile Discrimination Performance Using Voice Coil Actuators on the Forearm

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Abstract: What are the effects of frequency variation of vibrotactile stimuli on localization acuity? The precise localization of vibrotactile stimuli is crucial for applications that are aimed at conveying vibrotactile information. In order to evaluate the ability to distinguish between vibrotactile stimuli based on their frequency and location on the forearm, we used a relative point localization method. Participants were presented with pairs of sequential vibrotactile stimuli at three possible locations on the forearm and asked to determine whether the second stimulation occurred at the same location as the first one in the pair or not. The stimulation frequency varied between 100 Hz, 150 Hz, 200 Hz and 250 Hz, which covers the range of frequencies that human observers are most sensitive to. The amplitude was kept constant. Our results revealed that the ability to discriminate between actuators remained unaffected by variations in the frequency of vibrotactile stimulation within the tested frequency range. The accuracy of the tactile discrimination task was heavily dependent on the location of the stimulation on the forearm, with the highest accuracy close to the wrist and elbow, locations that may serve as tactile anchor points. Our results highlight the critical role of stimulation location in precise vibrotactile localization and the importance of careful consideration of location in the design of forearm-mounted vibrotactile devices.

Keywords: vibrotactile stimulus; voice coil actuator; wearable device; vibratory stimulus; vibrotactile localization; vibrotactile frequency; vibrotactile discrimination



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1. Introduction

Technical advances over the last two decades have made wearable vibrotactile displays a very attractive option for various tactile presentation devices. Several variations of such devices have been introduced in both scientific papers and commercial products and a variety of vibrotactile stimuli can be conveyed within the same display [1–6]. Voice coil actuators have been widely used in such displays because of their numerous advantages [7], including their ability to be incorporated into fabric-based displays, making them portable and convenient to use. The use of arrays of these actuators, such as those employed in tactile sleeves, allows for the encoding of considerable amounts of information to users. Vibrotactile patterns can be presented by manipulating the sequencing of the vibrations across the actuators, enabling the presentation of a wide range of sensations to users. The use of voice coil actuators in wearable vibrotactile displays has opened up exciting possibilities for the development of novel and sophisticated haptic technologies [8,9].

Tactile feedback has proven to be a versatile tool for enhancing various sensory experiences. For instance, it has been employed to supplement auditory information, alert individuals to important signals, provide information to users of prosthetic devices, and even serve as a substitute for vision in devices designed for the visually impaired [10–13]. The versatility of tactile feedback arises from the fact that it can be easily integrated into a wide

range of devices and interfaces, enabling individuals to experience rich and meaningful haptic sensations that can greatly enhance their overall sensory experience.

One recent development in the field of haptic displays is the use of tactile arrays in the form of wearable sleeves. These sleeves are designed to contain a relatively large array of vibrotactile actuators that can be used to deliver complex and nuanced haptic information to the wearer [14–18]. Such applied use calls for precise understanding of how reliable the perception of the vibrotactile information is and the resolution afforded by vibrotactile displays. Accurate perception of haptic stimuli is crucial for the reliable transmission of complex information encoded as haptic cues. It is, therefore, essential to investigate the accuracy of localization of tactile stimuli under diverse conditions and determine the influence of different parameters such as frequency, amplitude, duration, and location on haptic performance.

Several studies have addressed how different vibrotactile stimulation affects the localization of tactile stimuli [19]. Wong et al. evaluated the localization and information transfer of five tactors placed in a vibrotactile sleeve along the volar forearm and found that the locations of two to three actuators arranged along the length of the forearm could be reliably discriminated by human users when only the location of vibration was varied [15]. Zhao et al. examined stimulation with variation in frequency and vibrotactile patterns [20], finding significant differences in accuracy for vibrations on the dorsal side of the forearm at two frequencies (30 Hz and 250 Hz). The accuracy was better for 250 Hz than 30 Hz [20], consistent with the results of Evarsson et al., who tested the optimal stimulation frequency for vibrotactile stimulation with L5 actuators on the wrist [1].

Several researchers have examined the impact of stimulus duration on tactile recognition accuracy and found significant variability, revealing that the duration of vibrotactile stimuli can significantly affect localization accuracy, with longer-duration stimuli generally leading to better performance [20,21]. Moreover, localization and discrimination of vibrotactile stimuli can differ by stimulation site as well as by the method used to deliver the stimulation, i.e., whether it is conveyed sequentially or simultaneously [22].

Another factor that can affect the results of tactile discrimination tasks is the method of stimulus presentation. The two-point threshold, which is a measure of the minimum distance at which two distinct points of contact on the skin can be perceived as separate stimuli, is typically measured using a pair of calibres or other devices that allow the experimenter to vary the distance between the two points of contact [23].

The two-point threshold is often used as an index of tactile acuity or sensitivity. Relative point localization, which we used in this study is, on the other hand, a method used to assess observers' ability to detect differences in the position of two tactile stimuli. In this task, two stimuli are presented on the skin and participants judge whether the second stimulus is in the same or a different location as the first one or they indicate the direction of the second stimulus relative to the first stimulus. This method is often used to assess the ability to perceive spatial details in tactile stimuli [24]. While both two-point threshold and relative point localization are measures of tactile sensitivity, they assess different aspects of tactile perception and results for the two measures are not necessarily the same. Results acquired with the relative point localization (rPL) method, as used here, are not directly comparable to other measurement methods, such as absolute point localization (aPL) [25] or two-point thresholds (2PT) [23].

Weinstein [26] found that spatial tactile acuity with the two-point threshold was two to four times lower than with the absolute point localization, although they were highly correlated. Results from the two-point threshold method cannot be directly applied to vibrating stimuli since decisions about whether one or two tactors are activated can be affected by additive tactor intensity. Even though many studies have used absolute point localization (aPL) [25,27]. Taken together, the ability to localize a point of vibrotactile stimulation may not accurately reflect relative spatial acuity [24]. Other reasons for discrepancies could reflect factors such as individual differences in sensory perception, variations in the contact force between the skin and the device, or location. Another possible reason could be

related to the design of the device, such as the size and spacing of the tactile elements and the frequency and amplitude of the signals being used. Additionally, the concentration of tactile receptors on the skin is not evenly distributed, leading to a difference in sensitivity to touch and discrimination ability [26]. Psychophysical studies specifically investigate differences in outcomes for relative vibrotactile acuity measurements with different factor types. Additionally, measurements of vibrotactile spatial acuity may depend on presentation direction because of directional anisotropies [28].

Another important finding is that tactile stimuli are most effectively perceived when presented near anatomical reference points, typically associated with the body's joints. In our case, with stimulation on the forearms, the elbow and wrist serve as anchor points. This concept of "anchors" or reference points was first proposed by Weber [23] and Boring [29], and subsequent studies have demonstrated that certain anatomical points on the body exhibit high sensitivity for localization [30–32].

The discrimination of vibrotactile frequency on both glabrous and hairy skin has been assessed [33]. For instance, one study compared discrimination thresholds for the fingertip (27.2 Hz) and forearm (33.9 Hz), revealing that discrimination was 20% more accurate on the fingertip [34]. Vibrotactile stimulation is detected by mechanoreceptors in the skin, and one type, the Pacinian corpuscles, is responsible for the detection and perception of high-frequency vibrations greater than approximately 80 Hz [35]. The density of Pacinian corpuscles is much higher in the fingertip's glabrous skin than in the forearm's hairy skin [36], which explains the higher vibrotactile frequency discriminability on the fingertip than the forearm.

It is important to note, however, that in certain contexts, the use of fingertips for tactile feedback may not be practical or desirable. For example, when developing devices designed for sensory substitution, the use of fingertips may be problematic as it can interfere with the user's daily activities. In such scenarios, alternative methods of delivering tactile feedback may need to be explored, such as the use of other parts of the body or specialized wearable devices. By carefully considering the context of use and the needs of the users, more effective and user-friendly tactile feedback solutions can be developed that enable individuals to better engage with their environment and achieve their goals [33,37]. Use of the volar forearm as a location for delivering vibrotactile stimuli has become increasingly popular in recent years, owing to several attractive features of this anatomical site. The forearm is a convenient site for delivering vibrotactile stimuli due to its accessibility, which makes it relatively easy to apply wearable devices and integrate vibrotactile feedback into various applications. This location is suitable for delivering high-resolution stimuli, and it is compatible with clothing-like forms for wearable devices. Additionally, the forearm offers a relatively large surface area for stimulation, which allows the delivery of precise and nuanced haptic sensations to users.

Furthermore, the use of the forearm as a location for delivering vibrotactile feedback is generally well-tolerated by users, making it a practical and effective option for a wide range of applications [38]. A number of studies are available where vibrotactile stimuli have been delivered to the volar forearm, and various actuator types and parameters have been used [1,16,17,34,39,40].

Cholewiak and Collins [27] investigated the effect of frequency on absolute point localisation in young and older subjects on the volar forearm, using long piezoceramic tactors. Differences in localization ability between younger and older persons were smaller than expected while the frequency changed between 100 Hz and 250 Hz. Our study investigated the effect of frequency on discrimination accuracy using a wearable vibrotactile sleeve on the dorsal forearm, keeping the amplitude constant while varying the frequency. We used voice coil actuators that enabled us to manipulate frequency and amplitude independently of one another. The actuators were used to provide parallel and lateral vibration on the forearm length. Results were obtained using the relative point localization method. We found no differences in discrimination accuracy by frequency variation between 100 Hz, 150 Hz, 200 Hz and 250 Hz with constant amplitude. Our study did not

investigate sensitivity differences by age (participants were young adults). Notably, studies of frequency variation on the forearm with pressure and electro-tactile stimuli [41] cannot be generalized to vibrotactile stimuli. Different types of actuators and tactors, stimulus signal differences and properties, stimulation locations, and signal presentation methods can all affect performance [12,28]. Additionally, results acquired with the relative point localization (rPL) method, as used in our study, are not directly comparable to other measurement methods, such as absolute point localization (aPL) [25] and two-point thresholds (2PT) [23]. The ability to localize a point of vibrotactile stimulation may not accurately reflect relative spatial acuity.

Our research team has, in recent years, developed a series of vibrotactile displays, including the vibrotactile sleeve we examined in this study [1,12,16,17,37]. These displays have the potential to provide a vast amount of information to low-activity areas of the body, freeing up the hands for other tasks. This research has involved the investigation of several properties of vibrotactile stimulation in the context of sensory augmentation and sensory substitution [9,12,16,17,42–44].

The objective of the present study was to examine the discrimination accuracy for vibrotactile stimulation on the forearm as a function of frequency and location. Specifically, frequencies of 100 Hz, 150 Hz, 200 Hz and 250 Hz were employed while a constant vibration amplitude was maintained. This frequency range was chosen for two reasons: firstly, because of the high sensitivity of the Pacinian corpuscles to frequencies within this range, and secondly, because previous studies from our lab have demonstrated that this frequency range falls within the range of maximum tactile frequency sensitivity at the wrist [1]. We also investigated the effects of the location of the vibrotactile stimulation on the ability to discriminate between actuators and assessed any potential interactions with frequency.

2. Experiment

2.1. General Experiment Setup

The experiment was conducted in an anechoic chamber at the University of Iceland. Participants were seated on a chair in front of a laptop. The wearable vibrotactile sleeve was placed on the left forearm with the tactile actuators on the dorsal side. Participants placed their forearms on a foam pad (on a table) with the palm facing down. Their view of their left arm was blocked by placing foam in the line of sight to prevent any potential visual biases in responses (such as from visible vibrations).

To prevent audible cues from the tactile actuators, white noise was played through over-ear headphones to mask any sounds made by the actuators. Vibrotactile stimuli were delivered to the forearm via three voice coil actuators (Model: Lofelt L5, see Figure 2a).

Acceleration measurements were used to calibrate the intensity of the vibrotactile signal before recording data for each participant. A three-axis accelerometer (Brüel & Kjær Type 4520) was used to measure the acceleration of the vibration and calibrate its intensity.

To guarantee consistency and eliminate any sources of bias, this calibration process was performed individually for each participant prior to commencing the discrimination testing. Calibrating the vibrotactile sleeve on each participant's forearm enabled us to ensure that the same signal strength was perceived against the skin throughout the duration of the experiment.

Force measurements were also taken at the contact surface of enclosures and the skin of the forearm using a Force Sensitive Resistor (FSR), series FSR03, (Ohmite Manufacturing Company, Warrenville, IL, USA), and was obtained at 1.64 N. Table 1 provides the acceleration magnitude of the signal at the different frequencies used in the experiment.

Table 1. Amplitude and acceleration magnitudes across all frequencies in the study.

Frequency (Hz)	Acceleration (g)
100	9.6
150	7.6
200	6.9
250	6.7

We measured the forearm length of each participant, (four males and four females), and this information is presented in Table 2.

Table 2. The left forearm length measurements.

Participant	Gender	Length of Forearm (cm)
1	Female	21.04
2	Female	22
3	Female	22.5
4	Female	21.8
5	Male	23.8
6	Male	24.03
7	Male	24
8	Male	25

The study participants did not have significant differences in forearm length, so the average forearm length was used as a parameter to obtain biometric information. The average forearm length of the study participants was 23.3 cm. Figure 1 shows the biometric dimensions of the actuator placement along the forearm.

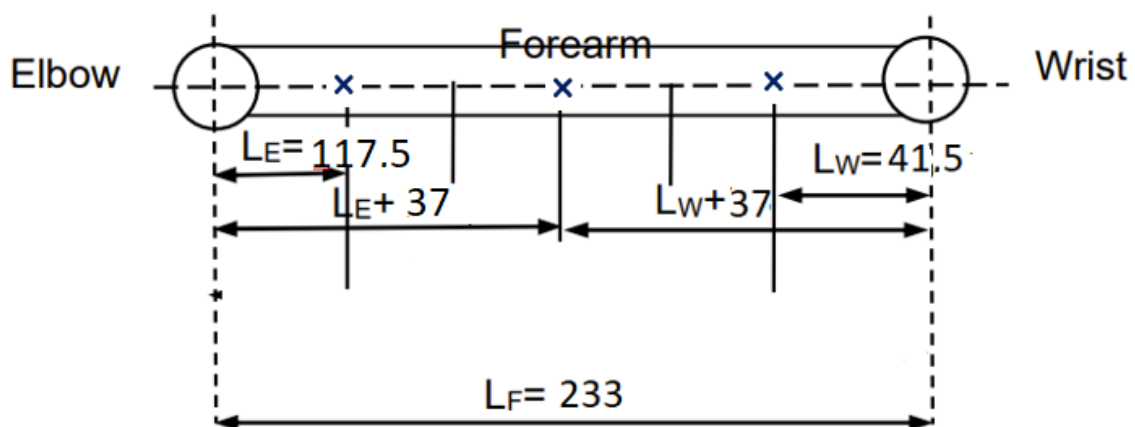


Figure 1. The biometric measurements utilized to determine the placement of the three actuators (×) along the forearm were derived from the average forearm length of the eight participants in the experiment. The centre points of the actuators were used for precise measurement. The inter-actuator distance was 20 mm, while the voice coil width was 17 mm. The distance of the centre point of the first actuator from the wrist was 41.4 mm, which accounted for the 33 mm stretch strap width and an extra 8.5 mm dimension from the centre of the first actuator.

The voice coil actuators were powered and controlled using audio hardware connected to a laptop computer, where custom-written Python code controlled the stimulus

presentation. The actuators were connected to the audio hardware via wired interfaces. The audio hardware consisted of a digital audio interface (RME MADIface XT) [45], digital-to-analogue converters (Ferrofish A32), multi-channel amplifiers, and parallel vibrating voice coil actuators (Lofelt L5) [7]. Using this setup, up to 32 tactile channels can be controlled independently. Tactile actuators were placed on the dorsal forearm in the longitudinal direction which caused back-and-forth vibration perpendicular to the forearm length. Before the start of the main experiment, the participants completed a few training trials to familiarize themselves with the setup, apparatus, and tactile stimulus.

2.2. Actuators

The tactile stimulation was generated using voice coil actuators, specifically the Lofelt L5 model (as shown in Figure 2a,b). The L5 actuator is an extended-band type of actuator that enables the independent manipulation of stimulation frequency and amplitude and is widely used in the implementation of haptic stimulation for scientific purposes [18].

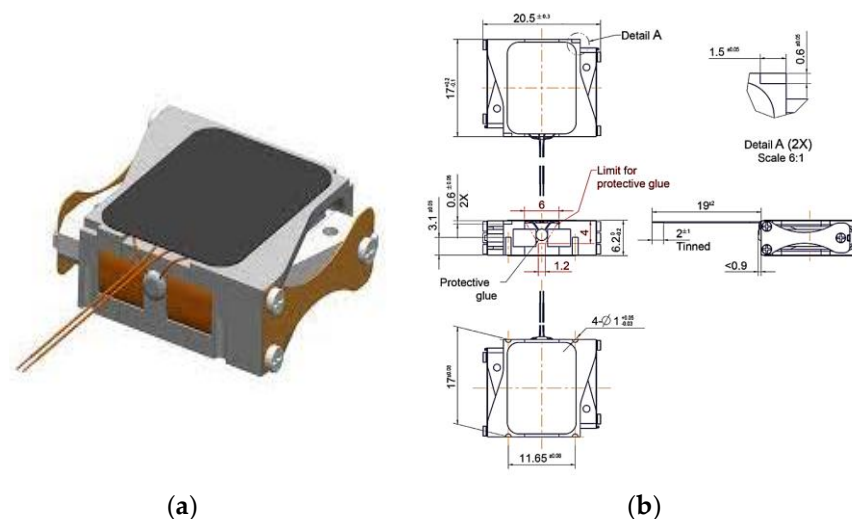


Figure 2. (a) The voice coil actuator (Model: Lofelt L5) used in this study; (b) Technical details and information about the spatial dimensions of the L5 voice coil actuator [7].

The L5 actuator is characterized by its high acceleration and efficiency, lightweight design, and cost-effectiveness, rendering it suitable for a range of vibrotactile displays, as outlined in Table 3. Furthermore, the Lofelt L5 voice coil actuator can produce vibration parallel to the skin, comprising tangential vibration [7].

Table 3. Haptic, electrical, and acoustic characteristics of the Lofelt L5 actuator [7].

Maximal voltage	1.4 Vrms at f0
Resonance frequency (f0)	65 Hz $\pm$ 5%
Frequency range	Min. 0.5 G over 35 Hz to 1 kHz
Nominal impedance	8 Ω at f0
Power handling	Maximum: 320 mW
Current consumption	Average at medium volume: 10 mA, bass music use-case Average at maximum volume: 57 mA, bass music use-case
Rise/stop times, 30 g attached mass, no DSP	5 ms/20 ms @ 150 Hz 12 ms/30 ms @ 100 Hz 15 ms/61 ms @ f0 18 ms/50 ms @ 50 Hz

The L5 actuators were placed in an enclosure that was specifically designed for the haptic sleeve. Several versions were tested for the enclosure design, and the final design was 3D-printed directly onto the fabric (Figure 3a,b). The purpose of the housing/enclosure was to prevent the actuator from coming into contact with other objects, which could dampen the vibrations. The physical dimensions of L5 actuators are $W: 17.0 \times D: 20.5 \times H: 6.2$ mm, and when they are vibrating at maximum displacement, their dimensions are $W: 17.0 \times D: 25.5 \times H: 6.2$ mm (the actuator may not be vibrating at its maximum, but it can do so). The dimensions of the enclosures were $W: 17.0 \times D: 28 \times H: 6.2$ mm (see Figure 3a).

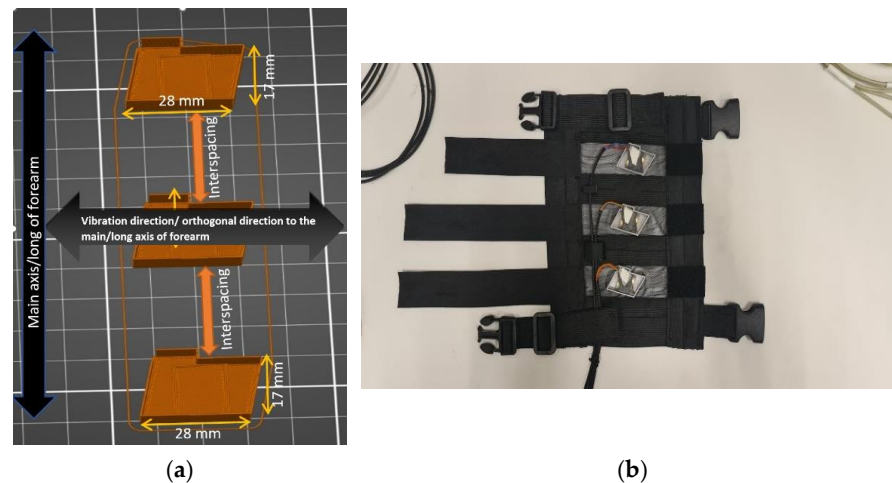


Figure 3. (a) Overview of the design of the sleeve used to apply the Lofelt L5 actuators along the forearm; (b) An example of a wearable vibrotactile sleeve and the configuration of the actuators.

2.3. Vibrotactile Sleeve

A soft and thin fabric-based vibrotactile sleeve was specifically made for this experiment. The tactile sleeve was made from a Power Mesh fabric (Power Mesh fabric material: 90% nylon and 10% spandex), which made the wearable sleeve comfortable and user-friendly. Stretch straps with Velcro were used to secure the haptic sleeve onto the forearm and make it easy to adjust according to the thickness of the user's forearm (see Figure 3b). The wearable tactile sleeve consisted of three voice coil actuators (Lofelt L5) placed in the 3D-printed enclosures printed onto the fabric. The fabric works as a scaffold to hold the actuators on a flexible and elastic surface.

A Prusa Slicer and a Prusa MK3s 3D printer were used for printing the actuator enclosure (PLA material (polylactic acid)). The coefficient of friction (COF) of PLA material can vary depending on several factors, such as the printing conditions ranging from 0.16 to 0.28. The actuators were firmly fastened inside the enclosures using glue [46]. Notably, there were no fabric layers between the enclosure and the skin (point of contact).

The tactile stimulation from the L5 actuators involves back-and-forth vibration parallel to the skin's surface. One benefit of the enclosure that we designed is that it keeps the moving part of the L5 actuator from scratching against the participants' skin or causing damage to the elastic material. The actuator is positioned inside the enclosure and designed to generate parallel vibration to the skin perpendicular to the forearm's length. The enclosure is crucial to ensure that the participant's skin and elastic material are not harmed during testing while enabling the actuator to stimulate the skin effectively through a smooth, lightweight, and thin (approximately 1.6 mm) enclosure surface. Since the actuator adheres to the enclosure, the actuator and the enclosure can function as a single unit. The vibration from the actuator is transmitted directly through the enclosure surface to the skin. This prevents the sharp edges of the voice coil actuators from irritating or harming the participant's skin or damaging the fabric during vibration.

The enclosures were placed along the dorsal forearm in a 3×1 array (longitudinal orientation) perpendicular to the forearm's length (Figure 3a,b). The spacing between

the actuators was 20 mm. The decision to use this distance was based on our previous study [17], which was carried out to determine the spacing between voice coil actuators that provides the highest localization accuracy when design convenience with L5 actuators is considered.

2.4. Participants

Eight participants (four females and four males, aged between 23 and 37) took part in the study. All participants were right-handed and had normal haptic perception by self-report. They were healthy adults and did not report any cognitive or sensory impairments that could potentially affect their ability to complete the tasks. Before participating in the study, each participant signed a written consent form. The study was conducted in accordance with the requirements of the local ethical committee and the Declaration of Helsinki.

2.5. Procedure

The study was aimed at investigating whether the frequency of tactile stimuli on the forearm has any effect on the participant's localization acuity. Each participant was presented with 96 tactile pairs. Each tactile pair consisted of two sequential tactile stimuli provided by the actuators. The duration of each tactile stimulus was 250 ms, and the inter-stimulus interval was 100 ms. Ensuring accurate adjustment of stimulus duration requires consideration of the system's rise and stop times.

These times reflect the duration required for the system to attain a steady-state response upon stimulus onset or offset. In our study, we employed a vibration stimulus burst of sufficient magnitude to achieve a steady-state condition for all four frequencies. Since the aim was to investigate the effects of frequency by location, amplitude was kept constant during the study. For each pair, the actuators for the first and the second stimulus (S1 and S2) were randomly and independently selected—i.e., a pair could also involve the same actuator vibrating twice. Frequencies for the first and second stimulation were randomly selected from 100 Hz, 150 Hz, 200 Hz, and 250 Hz, again based on the results of a previous study from our lab [1], where the maximum sensitivity to vibrotactile stimulation at the wrist was measured.

After each tactile pair was presented, participants were asked to report whether the pair was provided by the same actuator or came from two different actuators (2AFC paradigm). Observers responded by pressing one of two keys on a numeric keypad on the table in front of them within the allocated response time (in the intertrial interval between the presentation of each tactile pair—maximum 2000 ms). Once they provided feedback or if more than 2000 ms had passed from the presentation of the pair of tactile stimuli, a new pair of vibrotactile stimuli was presented (Figure 4).

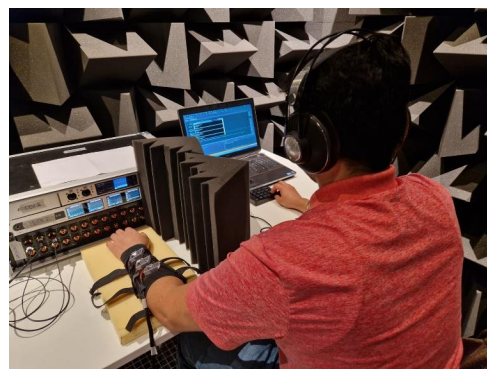


Figure 4. A participant wearing a vibrotactile sleeve with his hand on the cushion, using the headphones (playing white noise) to block out external auditory cues. Another cushion prevented observers from seeing their left hand. Observers responded to whether the vibrotactile stimulation was in the same or different locations by pressing the corresponding key on the wireless keyboard.

3. Results

We used a 2AFC paradigm to investigate how the frequency of vibration of each stimulus and its stimulation location affects the localization accuracy for pairs of vibrotactile stimuli. The observers' task was to indicate whether the two stimulations occurred in the same location or not, and the main variable of interest was the accuracy on this task.

The overall findings (in this case, irrespective of whether the stimulation was S_1 or S_2) are shown in Figure 5a,b. Figure 6 shows the results broken down by the frequency of the first stimulus (First stimulus (S_1) in the panels and Second stimulus (S_2) shown by the different dots). A three-way ANOVA analysis was conducted to examine the effects of three independent variables: (1) the frequency of the first stimulus (S_1), (2) the frequency of the second stimulus (S_2), and (3) the location of the stimuli on the accuracy of localization.

The ANOVA revealed a main effect of location ($F(2, 18) = 20.58; p = 0.00002$). No effects of frequency (neither for S_1 nor S_2) were significant, nor were any interactions significant (all p -values > 0.54). These findings clearly demonstrate that the location of the stimulation had a significant effect on the accuracy of judgments of whether one or two different sites were stimulated in the sequence, as the large effect of location from the ANOVA clearly demonstrates. Specifically, the accuracy was significantly higher when both stimuli were presented on the actuators adjacent to the wrist and elbow (see Figure 5a). Conversely, when there was a displacement between the wrist and middle (e.g., S_1 appeared at the wrist and S_2 appeared in the middle or vice versa), when there was a displacement between S_1 and S_2 from the elbow to the middle or vice versa, or when both stimuli were presented on the middle actuator, the accuracy decreased to a range of 71.25% to 79.25% (Figure 5a).

Participants were better at localizing stimuli when they were presented at the end-points of the array, i.e., the wrist and elbow, which, we speculate, operate as anchor points (see Introduction). Notably, the study revealed that the frequency of S_1 and S_2 did not have a significant effect on the accuracy of stimulus discrimination distinction, as revealed by the p -values of 0.81 and 0.65, respectively. The three-way interaction was also not significant. Moreover, there were no significant interactions between these stimuli and the location of the stimulus, as the p -values of 0.57 and 0.64 show, respectively.

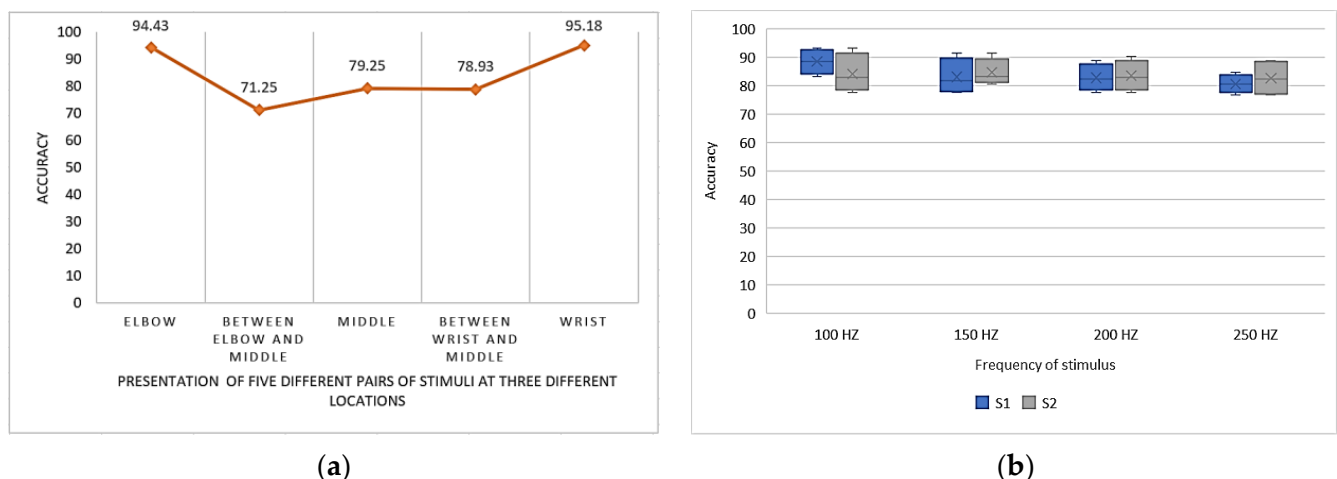


Figure 5. (a) The discrimination accuracy as a function of stimulation on the forearm. Three actuators were placed at three locations along the forearm: one close to the wrist, one close of the elbow, and one in the middle (see Methods). The stimuli were presented in five different pairs, consisting of (1) both stimuli presented on the wrist, (2) both stimuli presented near the elbow, (3) both stimuli presented on the middle actuator (middle), (4) where the first stimulus (S_1) was presented on the middle and the second stimulus (S_2) on the wrist or vice versa (displacement between wrist and middle), and (5) conditions where the first stimulus (S_1) was presented on the middle and the second stimulus (S_2) on the elbow or vice versa (displacement between elbow and middle). (b) The accuracy distribution for S_1 and S_2 as a function of frequency.

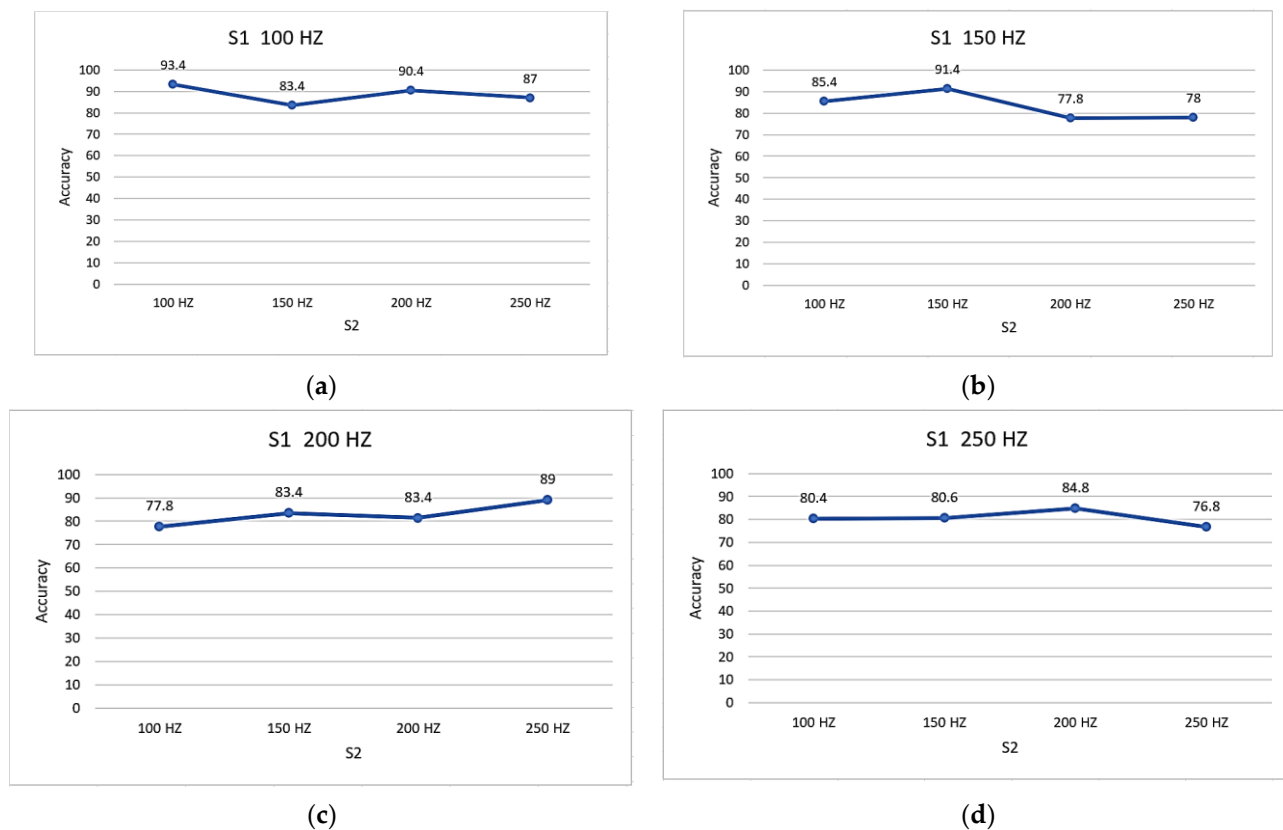


Figure 6. The average percent correct for different frequency combinations where the frequency of S₁ is denoted in different panels (a–d) and the different dots in each panel denote the frequency of S₂.

Overall, there was no statistically significant effect or interaction related to frequency, neither for S₁ nor S₂. This means that the frequency of the stimuli had a negligible effect on performance for both S₁ and S₂, at least within the tested frequency range (which, as explained above, should be optimal for vibrotactile stimulation), while the amplitude was kept constant. The average accuracy rate along the forearm ranged from 71.25% to 79.25%, which is notably lower than the accuracy rates near the wrist and elbow (94.43% and 95.18%, respectively).

The post-hoc analyses, with Bonferroni correction (*p*-values adjusted to 0.005; see Table 4), revealed statistically significant differences in localization accuracy and discrimination accuracy for the different stimulation locations, in particular showing how performance is best at the wrist and the elbow.

Table 4. The *p*-values from the post-hoc tests.

Groups Locations of Presenting the First and Second Stimulus	Displacement between Middle and Elbow	Middle/Middle	Displacement between Middle and Wrist	Wrist/Wrist
Elbow–Elbow	* 1.761×10^{-5}	* 7.748×10^{-5}	* 0.0001	0.358
Displacement between middle and elbow		0.033	0.0408	* 7.204×10^{-5}
Middle–Middle			0.462	* 2.406×10^{-5}
Displacement between middle and wrist				* 2.392×10^{-5}

* Significance at *p* < 0.005.

The results indicate significant differences in localization accuracy between tests where both stimuli came from the middle actuator compared to tests where both stimuli were presented on the actuator placed on the wrist ($p = 2.406 \times 10^{-5}$). Similarly, accuracy differed

significantly when both stimuli were presented on the middle actuator and when both stimuli were presented near the elbow ($p = 7.748 \times 10^{-5}$). Discrimination accuracy was also significantly different between tests where both stimuli were presented on the actuator placed on the wrist and tests where there was displacement between the middle actuator and actuator placed on the wrist ($p = 2.392 \times 10^{-5}$).

Additionally, significant differences in discrimination accuracy were observed when both activations were presented on the actuator placed on the wrist and where the stimulus displaced between the middle and the elbow ($p = 7.204 \times 10^{-5}$). Furthermore, the post-hoc test revealed significant differences in discrimination accuracy between tests where both activations were presented on the elbow and tests where stimuli were displaced between the middle and wrist ($p = 0.0001$). Similar significant differences were found between tests where the stimuli moved between the middle and near the elbow and tests where both activations were presented on the elbow ($p = 1.761 \times 10^{-5}$).

These findings suggest that the location of stimulation of different actuators in the sleeve has a strong effect on discrimination accuracy. In sum, these results suggest that the location of the stimulus is a critical factor in accurately distinguishing between stimuli in a haptic feedback system. The frequency had no effect on accuracy, however.

4. Discussion

The development of vibrotactile displays for augmenting perception or for sensory substitution makes the understanding of the mechanisms underlying human tactile perception very important. In order to optimize the throughput of stimulus parameters of the skin, it is important to investigate how many actuators can be placed within a particular region before their loci become indistinguishable and how various parameters can influence accuracy, and the effective conveying of information.

To address these challenges, we conducted an experiment where we compared the localization of a sequence of tactile stimuli at different sites on the dorsal side of the forearm: the wrist, along the forearm length between wrist and elbow, and next to the elbow. Our aim was to explore the effects of the dimensions of the 3×1 array of voice coil actuators on vibrotactile localization. Our data, using relative point localization, demonstrated that the location of stimulation along the forearm significantly influenced discrimination accuracy.

However, frequency variation with constant amplitude had a minimal effect on accuracy. The results showed that discrimination performance is worse when the stimulation was applied in the middle of the forearm, even when the second stimulus was displaced from the midpoint to the endpoints of the array. In contrast, when both stimuli were presented on the actuators adjacent to the wrist and elbow, discrimination accuracy was significantly better. This raises the intriguing possibility that vibrotactile discrimination is better close to anchor points (elbow and wrist) compared to the middle of the forearm. This may have important consequences for the design of vibrotactile displays since it suggests that if the stimulation points fall adjacent to natural anchor points (such as the wrist or elbow), performance will be considerably better at those sites when compared to localization for sites far from such loci.

This information about the effect of stimulus location on the forearm will be beneficial in the future design of vibrotactile displays. In particular, the findings offer valuable insights into the design parameters for forearm-mounted displays, including the configuration of actuators and inter-actuator spacing, which can clearly affect accuracy. Specifically, placing actuators near the wrist and elbow on the forearm may significantly improve how accurately information with vibrotactile feedback can be conveyed.

Our previous results [17] show that the optimal distance between actuators is around 20 mm when both performance accuracy and convenience of the design (with L5 actuators) are considered. However, further investigations are necessary to test the hypothesis that using denser actuator placements near the wrist and elbow or higher vibration amplitude for actuators placed along the forearm will improve accuracy. An interesting proposal for

future tests is whether there are anisotropies in vibrotactile localization on the forearm in that accuracy is higher close to the putative anchor points.

5. Conclusions

While achieving discrimination accuracy above chance levels may not necessarily guarantee effective information transmission, the required level of accuracy ultimately depends on the specific goals of a given application. Our experiment provides valuable insights into the design parameters of vibrotactile displays on the forearm, specifically regarding the configuration and placement of actuators. Stimulation location along the forearm strongly affects discrimination accuracy, while any effects of frequency variation (with constant amplitude) are minimal.

Our study has confirmed the findings of Cholewiak and Collins [27] regarding the positive effect of anatomical landmarks on higher discrimination accuracy. We used voice coil actuators (specifically the Lofelt L5 model) and our experimental setup to validate these results. These findings have significant implications for the design of efficient tactile displays. It is suggested that placing actuators near the wrist and elbow can enhance the conveyance of information through vibrotactile feedback. This information can be utilized to improve various aspects of tactile display design, including increasing the rate of information transfer, enhancing discrimination accuracy, and improving spatial localization.

Moreover, the experiment raises the possibility of investigating anisotropies in vibrotactile localization on the forearm. Further exploration is needed to determine whether using denser actuator placements near the wrist and elbow or employing higher vibration amplitude for actuators placed along the forearm can further enhance accuracy.

In sum, our study contributes to our understanding of the mechanisms underlying human tactile perception and provides valuable recommendations for the design of forearm-mounted vibrotactile displays. By incorporating these insights into the development process, it becomes feasible to create more effective and efficient systems that enhance the user's experience and interaction with tactile feedback, ultimately leading to improved performance and usability.

Therefore, this study advances our understanding of the factors that influence the effective transmission of vibrotactile information and may pave the way for the creation of more sophisticated haptic feedback technologies for forearm-mounted displays. Such development will only be successful with a clear understanding of the psychophysical properties of the perceptual mechanisms in question.

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