Sensitivity to Vibrotactile Stimulation in the Hand and Wrist: Effects of Motion, Temporal Patterns, and Biological Sex

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Abstract

Objective: We investigated the impact of low-tempo, repetitive hand movements on vibrotactile sensitivity by employing various temporal and spatial patterns in the hand and wrist area.

Background: The investigation of a human's ability to perceive vibrotactile stimuli during dynamic hand movements remains understudied, despite the prevalence of slow to mild hand motions in applications such as hand navigation or gesture control using haptic gloves in Virtual Reality (VR) and Augmented Reality (AR).

Method: We investigated vibrotactile sensitivity, analyzing the impact of various factors, including *Motion* (static and low-tempo repetitive hand movements), *Temporal Patterns* (Single or Double vibrations with varying offset times), *Tactor Placements* (hand and wrist), *Spatial Patterns*, and *Biological Sex*.

Results: Our study revealed that *Motion* significantly influences vibrotactile sensitivity in the hand and wrist areas, leading to reduced accuracy rates during dynamic conditions. Additionally, as the stimulus onset approached in Double vibrations, accuracy rates markedly decreased. Notably, Hand *Placement* resulted in significantly higher accuracy rates compared to the Wrist design.

Conclusion: Our findings underscore the impact of motion in reducing vibrotactile sensitivity on the back of the hand and around the wrist.

Application: This research has wide-ranging practical applications, particularly in the field of VR/AR experiences, rehabilitation programs, and accessibility solutions through the use of haptic gloves. Insights from our study can be harnessed to enhance the efficacy of haptic gloves in conveying vibrotactile cues within these contexts.

Keywords: Vibrotactile sensitivity, tactile suppression, hand motion, haptic glove

Précis: We studied the effects of dynamic hand movements on vibrotactile sensitivity in two *Tactor Placements* and five *Temporal Patterns*. The results indicate that hand motion significantly decreased accuracy rates to vibrotactile stimulus. The Hand *Tactor Placement* resulted in higher accuracy rates, as well as *Temporal Patterns* with a greater gap in their onset times. The accuracy rates were not significantly affected by either *Sex* differences or any interaction effects.

Introduction

Vibrotactile feedback has the potential to transmit simple to complex messages to different body sites. The hand region has been predominantly utilized for delivering vibrotactile feedback, due to its higher sensitivity to vibrations (Sherrick & Cholewiak, 1986) and versatility for different applications. Haptic gloves equipped with vibrotactile feedback have demonstrated wide-ranging applications in human factors research, including Virtual Reality (VR) (Vechev et al., 2019), Human-Robot collaboration (Casalino et al., 2018), rehabilitation (Estes et al., 2015; Masmoudi et al., 2021), and accessibility (Krishna et al., 2010; Kilian et al., 2022). Vibrotactile signals can be seamlessly integrated with minimal disruption to other sensory modalities, such as vision or hearing, following the Multiple Resource Theory (Wickens, 2002). Consequently, they have proven effective in delivering alerts or guidance when other sensory channels are already engaged or unavailable (Elvitigala et al., 2019; Schmuntzsch & Feldhaus, 2013). One actively explored area is motion guidance using haptic gloves, which holds significant potential for various applications. For instance, haptic gloves can be employed in guiding patients during the process of restoring hand and arm functions in rehabilitation programs (Wu et al., 2017) or assisting individuals with vision impairments in navigating both outdoor and indoor environments (Keyes et al., 2015).

Previous research has explored the transmission of complex information using multiple tactors with diverse vibration patterns across various body locations (Brewster & Brown, 2004). However, humans do not exhibit heightened sensitivity in perceiving different levels of vibrations (Schönauer et al., 2015), especially when multiple tactors are placed in proximity with minimal spacing (Kim & Ren, 2014; Zhao et al., 2020). The hand and wrist exhibit greater sensitivity to vibrotactile stimuli compared to other body locations (Karuei et al., 2011; Wilska, 1954; Elsayed et al., 2020; Sherrick & Cholewiak, 1986), attributed to a higher density of vibratory receptors in these areas (Sherrick & Cholewiak, 1986; Cholewiak & Collins, 2013). Despite the widespread use of hand and wrist locations for conveying complex information (Pezent et al., 2019; Elvitigala et al., 2019; Muramatsu et al., 2012; Paneels et al., 2013), there is insufficient evidence to suggest whether these locations provide adequate spacing for humans to perceive multiple vibrations without confusion (Collins et al., 2001; Hong et al., 2017).

Furthermore, while haptic glove applications predominantly involve frequent hand movements, such as exploring objects in VR (Giannopoulos, Pomes, & Slater, 2012; Martínez, García, Oliver, Molina, & González, 2014; CyberTouch, 2017) or playing exergames (Schättin et al., 2022; van Hedel, Häfliger, & Gerber, 2016; Gerber, Kunz, & van Hedel, 2016), there remains insufficient research on investigating vibrotactile sensitivity when the hand is in motion. This is particularly crucial, since movement in these applications may result in tactile suppression (also known as tactile attenuation or tactile gating), which refers to reduction in vibrotactile sensitivity during motion (Juravle et al., 2011). Various body parts have been studied for vibrotactile sensitivity during physical movement, including the upper arm (Sanderson et al., 2022; Karuei et al., 2010; Gomes et al., 2020), forearm (Schönauer et al., 2015; Chen et al., 2018), fingers (Juravle et al., 2010), wrist (Karuei et al., 2010; Pakkanen et al., 2008), and thigh (Karuei et al., 2010). However, despite many haptic gloves incorporating vibrotactile tactors on the dorsal part of the hand (Yu et al., 2016; Zhao et al., 2020; Günther et al., 2018; Bahrin et al., 2023; Lehtinen et al., 2012), this area has not been extensively studied for tactile suppression in relation to hand motion. It is essential to address this gap, as compromised vibrotactile sensitivity due to hand motion (Ryu & Kim, 2004; Louison et al., 2017; Kaul et al., 2017) could potentially undermine the functionality of haptic gloves.

Temporal patterns are another important consideration, as several studies have revealed heightened sensitivity when incorporating longer intervals between two or more vibrations in various body locations (Shah et al., 2019; Boldt et al., 2014; Stronks et al., 2016). Simultaneous activation of multiple tactors has shown to yield diminished recognition rates, especially when tactors were affixed to forearm regions (e.g., achieving recognition accuracy of 54.2% and 82.9% for four and three simultaneous stimuli, respectively), in contrast to more sensitive areas such as the fingers (e.g., achieving a recognition rate of 93.0%) (Chen et al., 2018; Elvitigala et al., 2019). As an alternative approach, the Overlapping Spatiotemporal stimulations (OST) method (Luzhnica et al., 2016), which encodes varying onset times of multiple vibrations, has been proposed as an effective means of conveying complex patterns. While longer intervals (exceeding 100-120ms) between multiple vibrations or utilizing the OST method have been identified as effective approaches (Luzhnica & Veas, 2017; Korres et al., 2018), it remains uncertain whether such intervals provide adequate duration for the hand in motion.

There may also be a potential effect on vibrotactile sensitivity from biological sex; however, no strong consensus has emerged. Some studies suggest that women are more sensitive to vibrations in their hands (Gescheider et al., 1994), particularly during both static and dynamic hand movements (Post et al., 1994). However, other studies have found no significant difference in sensitivity based on sex, especially when vibrotactile signals were presented on the wrist, upper arm (Bikah et al., 2008), or middle fingers (Seah & Griffin, 2008).

The primary objective of this study was to examine the impact of hand motion on vibrotactile stimulus perception. Specifically, we examined how factors such as motion, temporal patterns, tactor placements, spatial patterns, and an individual's sex contribute to the perception of vibrotactile stimuli. We hypothesized that sensitivity to vibrotactile stimuli would be decreased under the following conditions: 1) when a hand is in motion; 2) when two vibrations are presented with a shorter onset time difference; and 3) when vibrations are transmitted to a wrist location as opposed to a hand. Additionally, we explored potential sex effects on sensitivity. The findings of this study were intended to provide recommendations and guidelines on the future development of haptic glove applications involving hand motion. These applications could include haptic-based systems that provide timely alerts while conducting physical activities, as well as haptic devices utilized in AR/VR settings to provide additional information or enhance presence.

Methods

Participants

A convenience sample of 22 young and healthy participants, sex-balanced with 11 males and 11 females, was recruited from the university and local community to take part in this study. The male participants had a mean (SD) age of 22.0 (4.8) years and the female participants had a mean (SD) age of 20.7 (2.2) years. To be eligible for the study, participants had to be 18 years or older, had normal to corrected normal vision, and be right-handed, as assessed by the Edinburgh handedness questionnaire (Oldfield, 1971). This research complied with the American Psychological Association Code of Ethics and was approved by the Institutional Review Board (IRB) at Virginia Tech (IRB #: 22-694). Written informed consent was obtained from each participant prior to participation. Participants were compensated either with cash at a rate of US$10 per hour or through course credit.

Experimental Procedures

Participants wore a custom-made haptic glove (Figure 1b) that had four commercial eccentric rotating mass coin vibration motors (Zhejiang Yuesui Electron Stock Co., Ltd, China), operating within a voltage range of 2-3.6V. The maximum voltage level was used while keeping the frequency constant at 220 Hz, which aligned with optimal sensitivity (150-300 Hz) as reported in the literature (Jones & Sarter, 2008; Günther et al., 2018). Moreover, we conducted pilot tests using different frequency levels before the experiment to validate our selection. An ESP32-S2 Arduino board (Espressif Systems, China) was interfaced with a laptop via a USB cable for seamless control of the vibrotactile stimuli. Each vibration pattern was initiated in response to a singular keystroke executed by the experimenter. To facilitate uninhibited hand movement during the dynamic condition, the Arduino board was affixed to the forearm using a flexible strap. To ensure participant comfort and safety, each tactor was housed within a dedicated 3D-printed compartment, and then affixed to the skin using hypoallergenic medical tape. This arrangement effectively prevented direct skin contact between the tactors and the accompanying wiring.

In each trial, one or two tactors would vibrate while the participants' hands were stationary or moving. Participants were informed at the beginning of the experiment that they would receive Single or Double vibrations at the location of the hand or wrist. They were asked to verbally report the location of the tactor(s) with which they perceived the vibration(s), referencing a printed copy of Figure 1a, which was recorded by the experimenter. The sequence of vibrations did not matter, so either "a and c" or "c and a" was considered correct for the a-c pair. The experiment session lasted approximately 40 minutes, with a brief intermission between each trial. Participants were provided 5-10 minutes of practice trials. To minimize auditory cues that might reveal tactor positions, a white noise (rain sound) was played through headphones during the trials.

Experimental Design

The within-subject design comprised a full factorial of four independent variables:*Motion* scenarios, *Temporal Patterns*, *Placements*, and *Spatial Patterns*. Each participant completed a total of 80 trials (2 *Motion* x 5 *Temporal Patterns* x 2 *Placements* x 4 *Spatial Patterns*) without repetition.

For a Single vibration, either a, b, c, or d represented different spatial patterns. Subsequently, Double vibration conditions were tested with a pair of tactors (i.e., a-c, a-d, b-c, b-d). The order of trials was counterbalanced between participants for the *Tactor Placements*, ensuring that half of the participants began the experiment with the Wrist and the other half with the Hand. Within each participant and *Tactor Placements*, Single vibrations with four randomly assigned *Spatial Patterns* were presented first, followed by randomized combinations of Double vibrations and *Spatial Patterns*. Furthermore, *Motion* levels were counterbalanced within combinations of *Tactor Placements* and Single and Double *Temporal Patterns* across participants.

Motion: Participants were subjected to two hand movement settings: static and dynamic conditions. In the static condition, participants maintained their hand and arm at rest on the table. In the dynamic condition, participants were instructed to move their hand between two designated X marks on the table, spaced 30 cm apart (refer to Figure 2). This movement occurred at a fixed speed of 27.5 cm/s (low-tempo), guided by a metronome beat set at 55 BPM. The distance of 30 cm was determined from pilot tests to allow continuous hand movement without requiring upper arm movement. The velocity of 27.5 cm/s was selected based on previous research examining hand interaction with virtual objects, where movement speed rarely exceeded 30 cm/s with various types of hand movement (Osawa, 2006). Participants synchronized their hand movement with auditory cues, alternating between the left and right X marks with each beat. Vibrations were provided during the third transition between the two X marks, starting from the right-side X mark.

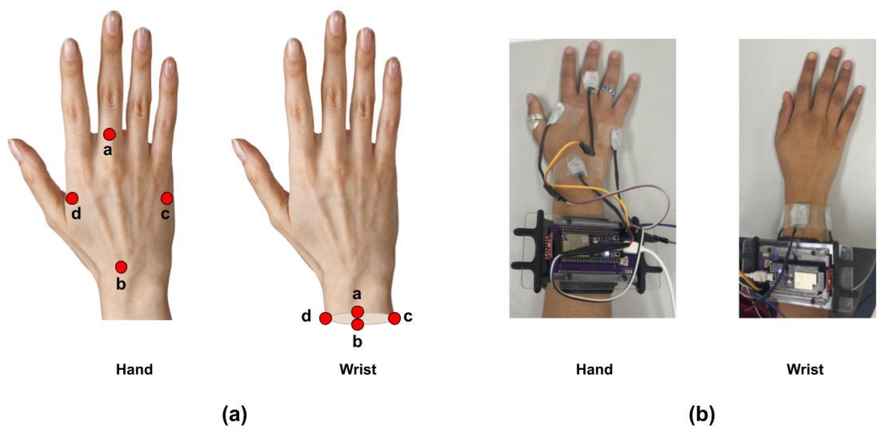

Figure 1: Four tactor locations on each hand and wrist *placement* (a); example pictures of participants wearing the glove (b).

Temporal Patterns: Five different vibration patterns were designed and used. With the exception of one temporal pattern, which consisted of only one vibration (referred to as Single), the subsequent four conditions involved two sequential vibrations emanating from distinct tactor locations with varying time gap. These conditions are referred to as Double throughout this manuscript, with different onset time intervals of 2 seconds (Double–2 s), 1 second (Double–1 s), 0.5 second (Double–0.5 s), and no interval (Double–0 s), as depicted in Figure 3. All vibrations were transmitted to a duration of 1 second to ensure that a single vibration with a static hand position, considered the easiest condition to perceive based on previous research, could be perceived without difficulties (Zhang et al., 2021; Gescheider et al., 1994; Dim & Ren, 2017). Consecutive (Double–1 s) and simultaneous (Double–0 s) patterns were selected based on their popularity in various applications (Liao et al., 2016; Afzal et al., 2016; Lee & In, 2023). An overlapping (Double–0.5 s) pattern was designed as an example OST. Lastly, a gap (Double–2 s) pattern was included as the easiest option between the two vibration conditions, providing sufficient offset between vibrations.

Placements: The hand and wrist locations were used for testing (Figure 1). The specific arrangement of the four tactor locations was informed by prior research demonstrating effective navigational performance using a diamond-shaped tactor placement (Yu et al., 2016). This configuration also resembles keyboard keys for up, down, right, and left directions, facilitating intuitive user perception. Similarly, the placement of tactors on the wrist was informed by previous applications on navigation (Hong et al., 2017), alarm display (Song et al., 2017), and enhancing VR/AR experiences (Pezent et al., 2019). In the hand design configuration, tactors were positioned at the dorsal side of the hand, with the proximal phalanx of the middle finger (a), between the Carpal bones on the wrist's dorsal side (b), the middle of Metacarpal bones on the ulnar (pinky) side (c), and on the radial (thumb) side (d). Conversely, the wrist design encompassed tactors encircling the wrist. Specifically, two tactors were positioned between the Pisiform and

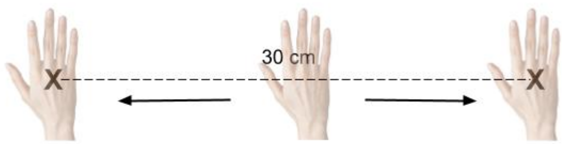

Figure 2: Hand movement during the Dynamic *Motion* condition.

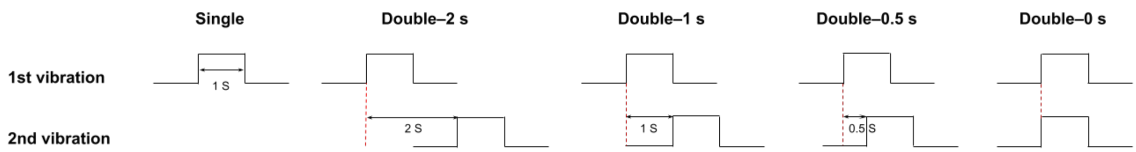

Figure 3: Temporal patterns for a Single or Double vibrotactile stimuli.

Scaphoid bones on both the dorsal side (a) and the ventral side (b) of the wrist. Another two tactors were placed at the respective ends of the ulna (c) and radius (d) bones. In order to accurately assess sensitivity to vibrations, the tactors were directly affixed to the skin rather than being attached to the glove. This approach was adopted to mitigate potential sensitivity alterations resulting from variations in glove fit, a facet not central to our investigation.

Spatial Patterns: Four different tactor locations were used to represent different spatial patterns. In a Single vibration condition, each tactor location (a, b, c, or d) represented a different spatial pattern. Double vibration conditions involved testing with a pair of adjacent tactors (i.e., a-c, a-d, b-c, b-d). For example, in a trial with a *Temporal Pattern* of Double–1 s and a *Spatial Pattern* of a-c pair, participants received a 1-second vibration at tactor location a, followed immediately by another vibration at location c as soon as the first vibration concluded. This study examined only the adjacent pairs, as they are frequently used in haptic-based navigation systems to convey diagonal movement directions (Satpute et al., 2019).

Statistical Data Analysis

Participants' responses were classified as accurate only when they correctly identified all instances of vibration occurrence in terms of location. Responses that correctly identified only one of the two vibration locations were considered as incorrect. To assess the influence of *Motion*, *Temporal Patterns*, *Tactor Placements*, and Sex on recognition accuracy, a nominal logistic regression analysis (Andersen, Morrison, & Knudsen, 2012) was used. This approach was chosen due to the binary nature of the recognition response (correct vs. incorrect). *Motion, Temporal Patterns, Tactor Placements*, and *Sex* were included in the analysis, and up to three-way interactions were investigated. Significant main and interaction effects were subjected to post-hoc pairwise comparisons, which were adjusted using the Bonferroni correction method. All statistical tests were performed using JMP Pro 16 (SAS, Cary, NC). Statistical significance was concluded at the $\alpha = 0.05$. Odds ratios (OR), along with their corresponding confidence intervals (CI), were computed for any identified significant effects (Please see Table A.1 in the Appendix). Due to the distinct arrangement of tactor locations across two *Tactor Placements*, meaningful comparisons of recognition accuracy across all *Temporal Patterns* and *Spatial Patterns* were deemed impractical. For instance, the *Spatial Pattern* of a-c in the Hand *Placement* refers to the proximal phalanx of the middle finger and the middle of Metacarpal bones on the ulnar side of the hand, whereas a-c in the Wrist *Placement* refers to the dorsal side of the wrist (between the Pisiform and Scaphoid bones) and the end of ulna bone. Thus, we deemed comparing a-c pairs in the Hand vs. Wrist *Placement* is not practically meaningful. Consequently, the nominal logistic regression analysis did not incorporate the main and interaction effects of *Spatial Patterns*. Instead, the effects of *Spatial Patterns* were evaluated within each combination of *Temporal Patterns* and *Tactor Placements*, as separate Chi-square tests ($\alpha = 0.05$), followed by post-hoc tests with Bonferroni correction for significant main effects. This allowed us to ascertain whether the sensitivity of each tactor location(s) exhibited any variations within specific conditions.

Results

The mean and standard error of recognition accuracy based on different *Tactor Placements*, *Motion*, and *Temporal Patterns* are depicted in Figure 4. Detailed recognition accuracy based on different *Spatial Patterns* can be found in the Appendix (Figure A.1). A nominal logistic regression result is also summarized in Table 1 with detailed post-hoc results provided in Table A.1. No significant interaction effects nor *Sex* effect on recognition accuracy were found. The remainder of this section will detail the three significant main effects that emerged from the test.

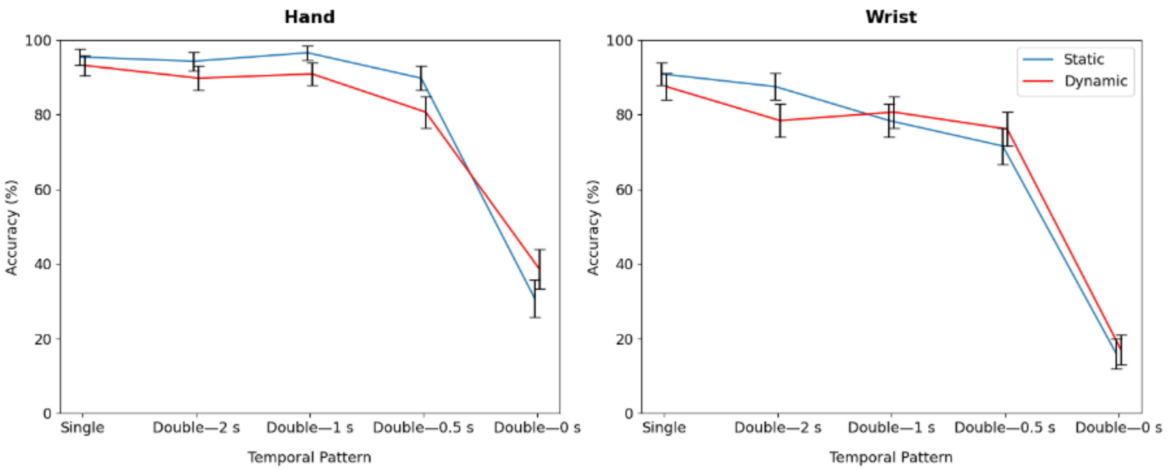

Figure 4: Recognition accuracy (%) across various *Temporal Patterns* for each *Placement* and *Motion* conditions. Error bars represent standard error. *N* in each *Placement* (Hand vs. Wrist) = 176 (Single); = 704 (Double).

Table 1: Summary of nominal logistic regression results, along with a summary of pair-wise comparisons in significant main effects. Note that significant effects are highlighted in bold font ($p < .05$).

Effect	Chi-Squared value	*p* value
Motion Static > Dynamic	**3.99**	**.046**
Temporal Pattern (Single, Double–2 s, Double–1 s) > Double–0.5 s > Double–0 s	**527.17**	**<.001**
Tactor Placement Hand > Wrist	**41.92**	**<.001**
Sex	0.45	.502
Motion × *Temporal Pattern*	4.898	.298
Motion × *Tactor Placement*	1.60	.206
Tactor Placement × *Temporal Pattern*	2.733	.603
Motion × *Temporal Pattern* × *Tactor Placement*	4.267	.371

Motion

Participants made more errors when identifying tactor locations during motion, confirming our hypothesis that vibrotactile sensitivity decreases when the hand is in motion. Specifically, the mean recognition accuracy during dynamic hand movement for all temporal patterns and tactor placements (73.2%) was significantly lower in comparison to the overall static hand movement condition (75.2%). According to Figure 4, while participants exhibited better performance in the dynamic condition compared to the static condition for certain combinations of *Temporal Patterns* and *Placements*, the lack of significance in the three-way interaction effect of *Motion*, *Temporal Pattern*, and *Tactor Placement* suggests that this difference in mean accuracy is not considered significant. Moreover, the static condition showed an increased odds ratio (OR) (1.36) compared to the dynamic condition, indicating that it is 1.36 more likely to be recognized correctly (Table A.1).

Temporal Pattern

We found a significant effect of *Temporal Patterns* on recognition accuracy. The overall accuracy declined as the time gap between the onsets of two vibrations decreased, supporting our hypothesis that there would be a significant decrease in vibrotactile sensitivity when vibrations are delivered with a shorter onset time difference (refer to Figure 4). There was no significant reduction in accuracy when comparing the scenario with two non-overlapping Double vibrations (Double–2 s and Double–1 s) to that with a Single vibration. However, a significant decrease in accuracy was evident when two vibrations had overlap (Double–0.5 s) or were simultaneously played (Double–0 s). There was also a significant decrease in accuracy rate from overlapping (Double–0.5 s) to simultaneous (Double–0 s) vibrations (Figure 4). In Double–0 s, the highest accuracy rate was observed with a tactor pair of a-d (38.6%), while a b-d pair resulted in the lowest accuracy rate (10.2%) (Figure A.1).

Tactor Placement

Tactor Placement had a main effect, in which recognition accuracy was significantly lower with the Wrist design (68.4%) compared to the Hand design (80.0%) (Figure 1), with an OR of 0.37 (Table A.1). This finding confirms our hypothesis that there would be a significant difference in vibrotactile sensitivity between the hand and wrist regions, with the wrist exhibiting significantly lower sensitivity. Additionally, in the Wrist *Tactor Placement*, the a-c tactor pair resulted in the lowest accuracy rate (53.4%) with double vibrations, while the b-c pair resulted in the highest accuracy rate (73.9%). However, in the Hand *Placement*, the highest accuracy rate in double vibrations belonged to the a-d pair (85.2%), and the lowest accuracy rate occurred in the b-d pair (Figure A.1).

Spatial Pattern

Separate analyses showed that *Spatial Pattern* was a significant main effect in two of the *Placements* and *Temporal Patterns* combinations (see Figure 5). Specifically, in the Hand *Placement* with the Double–0 s *Temporal Pattern*, the b-d tactor pairs exhibited significantly lower accuracy in comparison to the a-d (χ^2 = 21.60, df = 1, p <.0001) and a-c pairs (χ^2 = 14.76, df = 1, p = .0001). In the Wrist *Placement* with the Double–1 s *Temporal Pattern*, the a-c pair demonstrated a significantly lower accuracy compared to the b-c pair (χ^2 = 15.27, df = 1, p <.0001).

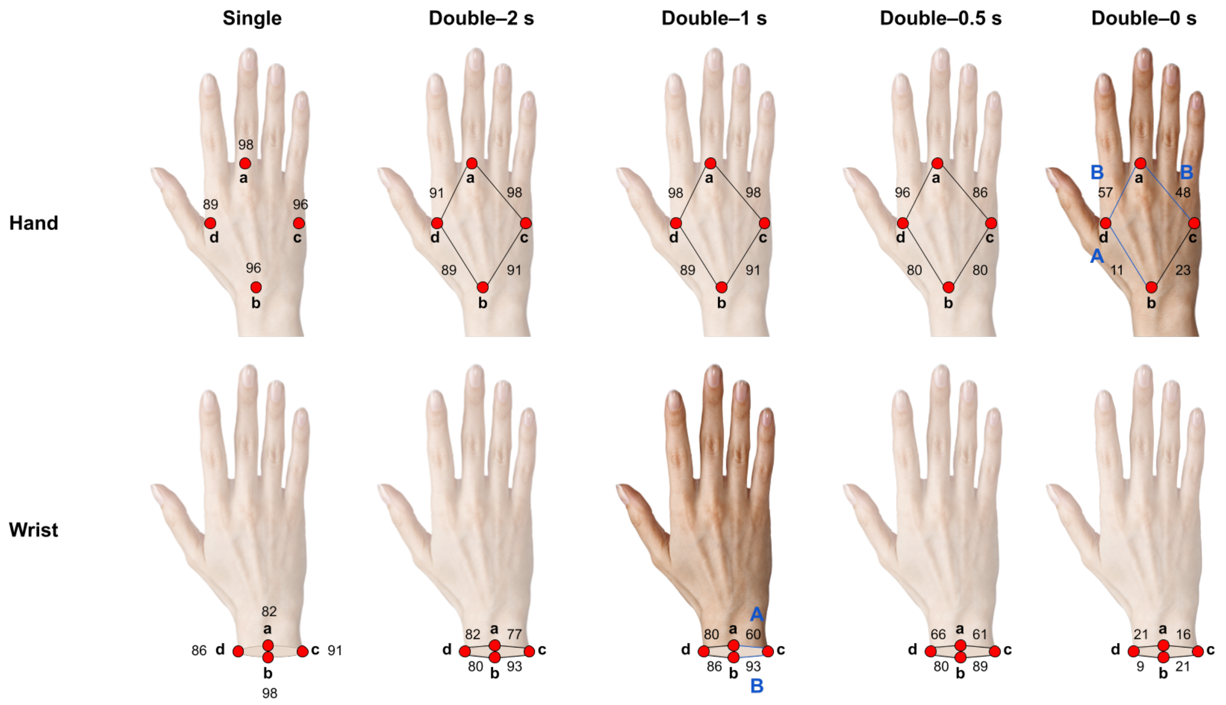

Figure 5: Recognition accuracy (%, represented as numbers) by *Spatial Pattern* for different *Tactor Placement* and *Temporal Pattern* conditions. Tactor pairs with significantly different accuracy are marked with different capital letters in each hand representation.

Discussion

We assessed vibrotactile sensitivity between the dorsal hand and the wrist region while the hand is in motion across various temporal and spatial patterns. The results of this study indicate that mid-tempo hand motion significantly impairs vibrotactile perception in the areas of the back of the hand and wrist. Our findings are consistent with prior research by Juravle et al. (2010), in which goal-directed hand movements resulted in reduced sensitivity to a single vibration stimuli during the execution phase, as compared to the motor preparation and post-movement phases. The current study contributes to this body of knowledge by incorporating additional tactor locations and factors, such as *Temporal Pattern, Tactor Placement*, and *Spatial Pattern*, beyond the use of a single tactor attached to the middle finger as described by Juravle et al. (2010).

During physical activity, including simulated low-tempo hand movement in this study, cognitive resources are divided to coordinate motor actions and process tactile information, as outlined by the multiple resource theory (Wickens et al., 2021). This phenomenon could explain tactile gating, which involves the suppression of tactile perception during movement. Previous research suggests that tactile gating is influenced by the speed of the movement (Cybulska-Klosowicz et al., 2011). In this study, the motion employed was a simple and repetitive movement along a predetermined path at a constant rate of 27.5 cm/s, which can be considered a relatively low-tempo movement. In a prior investigation that examined the effects of faster movements involving elbow extensions, researchers found that the mean critical speed at which tactile gating, defined as a detection rate falling below 50%, was observed, occurred at a movement speed of 47.2 cm/s when using a single tactor stimulus (Cybulska-Klosowicz et al., 2011). Given that our movement speed of 27.5 cm/s was lower than the critical speed observed in the previous study, it is reasonable to conclude that we started to observe tactile gating with two stimuli only during the *Temporal Pattern* of Double–0 s, involving two simultaneous vibrations. It is important to note that had the participants' hands engaged in more erratic or rapid movements, the detection accuracy could have deteriorated further.

We also observed a decline in accuracy rates when the onset points of two vibrations approached each other, as illustrated in Figure 4. This confirms our hypothesis that vibrotactile sensitivity would decrease when vibrations are presented with shorter onset time differences. The decline became statistically significant when the two vibrations began to overlap in time duration, as evidenced by *Temporal Patterns* Double–0.5 s and Double–0 s in Figure 3. This finding aligns with previous research that examined accuracy rates when multiple vibrations were presented with minimal to zero onset time gaps, particularly in the abdominal region (Faugloire et al., 2022). While this study did not reveal any interaction between the factors of *Temporal patterns* and *Spatial patterns*, prior research has shown that the recognition rate can decrease in relation to the inter-tactor distance. Specifically, tactile gating was observed with an inter-tactor distance of 9.5 mm with two simultaneous vibrations (Faugloire et al., 2022). Finally, our investigation determined that changes in *Temporal Pattern* do not interact with *Motion*, indicating that the detrimental effect of closer onset times between two vibrations impairs sensitivity, irrespective of *Motion*.

Our investigation into *Tactor Placement* within the hand and wrist regions contributes to extending understanding of the most effective locations for implementing haptic gloves. Notably, our findings revealed that placing the tactors in the Hand resulted in significantly higher accuracy rates than the Wrist, which supports our hypothesis. Several factors could account for this discrepancy, including anatomical differences in tactor placements, which has been extensively discussed by Sherrick and Cholewiak (1986). For instance, the distance between tactors in each design and the musculoskeletal structure beneath the skin, where the tactors were attached, could influence how easily vibrations are transmitted to nearby tactor locations, ultimately affecting tactile sensitivity in the region. The hand is recognized to have a reduced two-point threshold compared to the wrist (Cholewiak & Collins, 2013), a finding that aligns closely with our study results.

In the context of the simultaneous (Double–0 s) *Temporal Pattern* and Hand *Tactor Placement*, we observed significantly lower accuracy rates for the b-d pair (11%) compared to the a-d (57%) and a-c (48%) pairs, as shown in Figure 5. While the difference was not statistically significant, the b-c pair also exhibited relatively lower accuracy rates (23%) than the a-d and a-c pairs. One potential explanation for these variations is the placement of tactor "a" on the lower end of the middle finger, which creates structural separation (i.e., tactors are not attached on the same bone) from the tactors attached on the dorsal side of the hand (i.e., a, b, and c). Regarding the significantly lower accuracy rates of a-c compared to b-c in the combination of Wrist *Tactor Placement* and consecutive (Double–1 s) *Temporal Pattern*, this could be attributed to the higher density of Pacinian corpuscles on the palmar side of the wrist compared to the dorsal side, which influences tactile sensitivity (Johansson & Vallbo, 1979).

Our study did not reveal any statistically significant sex effect between males and females. This finding aligns with the limited number of studies that have investigated the influence of sex on vibrotactile perception across various anatomical regions of the body (Bikah et al., 2008; Neely & Burström, 2006). In a study conducted by Neely and Burström (2006), although it was observed that there was no statistically significant sex effect on sensitivity, females did report perceiving vibration intensity and discomfort to a greater extent than their male counterparts. While it is worth noting that one study reported that females showed greater perception rates to vibrotactile stimuli than males in the thenar eminence and digits of the hand during the process of isometric elbow flexion and extension (Post et al., 1994), a direct comparison with our study is challenging due to differences in the hand region and dynamic movements used in our respective investigations.

Several limitations are noteworthy to be mentioned. First, we maintained a fixed maximum strength level of intensity (5V) for all sensations during testing. Recognizing that perceived intensity depends on factors such as vibration amplitude and frequency (Choi & Kuchenbecker, 2012; Hwang et al., 2013), variations in stimulus intensity could lead to different accuracy rates, potentially with interaction effects between independent variables. Second, we did not record the response times, which could serve as a valuable secondary dependent measure for evaluating reaction time. The focus of this study was to understand the sensitivity (i.e., correct identification of the locations) of the vibrations, rather than the speed of the recognition. However, reaction times could be particularly important for assessing the efficacy of haptic glove designs in situations where rapid response or action is essential. Third, the participant sample was drawn from a convenient population of younger individuals. Therefore, the results of this study may not be generalizable to individuals of all age groups, as previous research has shown that sensitivity to vibration changes significantly as individuals age (Verrillo, 1980). Another limitation of this study is the small sample size, which resulted in a relatively low statistical power (0.65; calculated using G*Power software (Faul et al., 2009), based on effect size = 0.43, $\alpha = 0.1$, n = 22, df = 1) for the motion variable. Future studies should include a larger number of participants to reduce type I error. Ultimately, listening to a metronome beat during hand movement may have introduced additional cognitive processing demands. However, we did not specifically investigate whether these additional auditory tasks influenced the reduced sensitivity observed in the hand movement condition.

Future research is advisable to explore the sensitivity in faster or non-repetitive hand movements and their impact across different types of motion. Additionally, there is a benefit in examining response times under similar conditions to ensure that the heightened sensitivity observed in certain scenarios correlates with quicker response times, particularly crucial for time-sensitive applications. Assessing sensitivity across diverse age groups would also be valuable, given the decline in sensitivity associated with aging and the increasing utilization of accessibility technologies among older populations. Finally, various other factors may influence vibrotactile sensitivity, including room or body temperature (Klinenberg et al., 1996) and different hand postures (e.g., making a fist vs. an open hand). Future research could assess the impact of these factors to explore alterations in vibrotactile sensitivity under more diverse conditions. Our findings hold practical significance, offering valuable insights for a range of future applications employing haptic gloves or wristbands with low-tempo hand movements. These applications span various domains, including but not limited to spatial navigation and guidance in real-world or VR/AR environments, navigation systems, rehabilitation and exercise programs.

Conclusion

In this study, the impact of repetitive, low-tempo hand movements on vibrotactile sensitivity was investigated. Our results demonstrated that motion has a significant damping effect on vibration sensitivity across all *Temporal patterns* and *Tactor Placements*. Moreover, the *Temporal Patterns* played a pivotal role in affecting accuracy rates, with a notable decrease in rates as the onset point of double vibrations had shorter time gaps. Additionally, the diamond-shaped Hand *Tactor Placement* exhibited significantly higher accuracy rates in comparison to the Wrist design. In summary, our findings suggest that attaching tactors around the dorsal side of the hand with adequate spacing between them would be advantageous, particularly with an offset time greater than 0.5 – 1 seconds for double vibrations. These findings hold practical value for human factors designers, especially in the context of haptic glove applications. Our results offer recommendations into scenarios that necessitate continuous, repetitive low-tempo hand movements, which are frequently encountered in AR/VR, navigation and rehabilitation applications. Particularly, our work can be useful for applications where users engage in hand movements to explore environments or in physical exercise.

Key Points

- Dynamic hand movements significantly decreased vibrotactile perception compared to static conditions.
- The placement of tactors on the hand led to greater perception compared to the wrist.
- As the time gap between the onsets of two vibrations decreased, the perception also diminished.

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Appendix A

Table A.1: Post-hoc test results for all significant main effects on mean accuracy (%).

IV	Pair	Odds Ratio, Confidence Interval	P-value
Motion	Static > Dynamic	1.36, [1.00, 1.84]	**.046**
Temporal Patterns	Single, Double–2 s	0.66, [0.38, 1.12]	.121
	Single, Double–1 s	0.68, [0.39, 1.19]	.177
	Single > Double–0.5 s	0.35, [0.21, 0.57]	**<.001**
	Single > Double–0 s	0.03, [0.02, 0.04]	**<.001**
	Double–1 s, Double–2 s	1.04, [0.62, 1.75]	.889
	Double–2 s > Double–0.5 s	0.53, [0.34, 0.83]	**0.005**
	Double–2 s > Double–0 s	0.04, [0.03, 0.06]	**<.001**
	Double–0.5 s > Double–1 s	0.51, [0.32, 0.82]	**.006**
	Double–1 s > Double–0 s	0.04, [0.03, 0.06]	**<.001**
	Double–0.5 s > Double–0 s	0.08, [0.05, 0.11]	**<.001**
Tactor Placements	Hand > Wrist	0.37, [0.29, 0.52]	**<.001**

Motion

Static

Single

N = 176		Perceived				
		a	b	c	d	Others
Actual	a	86.4	2.3	11.4	0	0
	b	2.3	97.7	0	0	0
	c	0	6.8	93.2	0	0
	d	0	2.3	0	95.4	2.3

Double

N = 704		Perceived				
		ac	bc	bd	ad	Others
Actual	ac	71	2.8	0	0	26.1
	bc	4.5	73.3	0	0	22.2
	bd	0	0	65.3	4.5	30.1
	ad	0	0.6	0	72.7	26.7

Dynamic

Single

N = 176		Perceived				
		a	b	c	d	Others
Actual	a	93.2	0	6.8	0	0
	b	0	95.4	0	0	4.5
	c	0	6.8	90.9	0	2.3
	d	6.8	4.5	0	79.5	9.1

Double

N = 704		Perceived				
		ac	bc	bd	ad	Others
Actual	ac	64.7	5.7	0	1.7	27.8
	bc	0.6	71.6	1.1	0.6	26.1
	bd	0	0.6	65.3	4.5	29.5
	ad	2.3	0.6	2.3	74.4	20.4

Temporal Pattern

Double–2 s

N = 352		Perceived				
		ac	bc	bd	ad	Others
Actual	ac	87.5	2.3	0	0	10.2
	bc	1.1	92	0	1.1	5.7
	bd	0	0	84.1	3.4	12.5
	ad	1.1	0	1.1	86.4	11.4

Double–1 s

N = 352		Perceived				
		ac	bc	bd	ad	Others
Actual	ac	78.4	9.1	0	0	12.5
	bc	3.4	92	0	0	4.5
	bd	0	0	87.5	3.4	9.1
	ad	0	2.3	1.1	88.6	7.9

Double–0.5 s

N = 352		Perceived				
		ac	bc	bd	ad	Others
Actual	ac	73.9	4.5	0	1.1	20.4
	bc	2.3	84.1	1.1	0	12.5
	bd	0	1.1	79.5	3.4	15.9
	ad	1.1	0	2.3	80.7	15.9

Double–0 s

N = 352		Perceived				
		ac	bc	bd	ad	Others
Actual	ac	31.8	1.1	0	2.3	64.8
	bc	3.4	21.6	1.1	0	73.9
	bd	0	0	10.2	7.9	81.8
	ad	2.3	0	0	38.6	59.1

Tactor Placement

Hand

Single

N = 176		Perceived				
		a	b	c	d	Others
Actual	a	97.7	0	2.3	0	0
	b	0	95.4	0	0	4.5
	c	0	4.5	95.4	0	0
	d	2.3	2.3	0	88.6	6.8

Double

N = 704		Perceived				
		ac	bc	bd	ad	Others
Actual	ac	82.4	0.6	0	1.7	15.3
	bc	2.8	71	1.1	0	25
	bd	0	0.6	67	4.5	27.8
	ad	0.6	0	0.6	85.2	13.6

Wrist

Single

N = 176		Perceived				
		a	b	c	d	Others
Actual	a	81.8	2.3	15.9	0	0
	b	2.3	97.7	0	0	0
	c	0	9.1	88.6	0	2.3
	d	4.5	4.5	0	86.4	4.5

Double

N = 704		Perceived				
		ac	bc	bd	ad	Others
Actual	ac	53.4	7.9	0	0	38.6
	bc	2.3	73.9	0	0.6	23.3
	bd	0	0	63.6	4.5	31.8
	ad	1.7	1.1	1.7	61.9	33.5

Figure A.1: Confusion matrices of vibrotactile sensitivity, where the number in each cell represents the % of correct recognition, are represented for various conditions of *Motion*, *Temporal Pattern*, and *Tactor Placement*.

Biographies

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