# Perception of paired vibrotactile stimulus on the upper limb: implications for the design of wearable technology

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**Abstract.** The ability to correctly perceive multiple stimuli represents an important barrier to the use of vibrotactile devices in training complex behaviors. The aim of this study was to evaluate how stimulation parameters influence perception of vibrotactile patterns applied to the forearm and upper arm. In this experimental protocol, participants (N = 16) were asked to compare two vibrotactile sequences and indicate whether they were the same or different. We examined the effects of (1) sequential versus simultaneous vibrotactile stimulation; (2) the temporal structure of the vibrotactile stimulus upon subject perception and (3) difference in pattern recognition between the two segments. Our results confirmed that perception was generally superior when the two stimuli were presented sequentially and when there was a marked difference in the temporal structure of the signals. At the same time, participants were highly capable of detecting two identical sequences when presented simultaneously. These findings may have important implications for the design of wearable vibrotactile devices intended for guiding upper limb movement.

**Keywords:** Haptic Technology, Vibrotactile Stimulation, Tactile Discrimination, Judgement, Tactile Pattern Recognition.

## 1 Introduction

Assistive technology increasingly uses tactile cues to influence or correct motor behavior. Broadly speaking, this involves transmission of a mechanical stimulus (e.g. pressure or vibration) to the user's body. Devices using augmented tactile feedback may take different forms, including instrumented objects or robotic comanipulation devices [1,2]. Vibrotactile matrices which integrate multiple vibrating actuators into a wearable garment are increasingly popular, with potential applications in navigation, behavioral training, and motor learning [3,4]. The basic premise of such devices is that the tactile stimulus confers information regarding the user's actions, and how they conform with the desired performance. In motor learning, feedback might indicate whether a particular goal has been achieved (i.e. knowledge of results). Alternatively, feedback may be used to provide knowledge of performance, that is to say, information regarding the coordination of movement and how that might be improved [5].

The appropriation of wearable vibrotactile devices for training motor skills across the health, industrial and sporting sectors, however, remains somewhat limited. In a recent systematic review, van Breda et al. found that learning effects when using these technologies were generally poor [6]. In relatively simple applications, such as using a vibrotactile system at the level of the wrist to guide hand movements in a two-dimensional plane, some benefits may be observed [7,8]. Similarly, vibrotactile feedback may assist in training the orientation of a given segment (i.e. forearm) in a simulated reaching task [9]. The benefits of vibrotactile feedback for improving knowledge of performance across multiple segments though, are yet to be proven. Certain authors have attempted to train more complex upper limb gestures, including those used in combat sports or use of musical instruments [9,10]. However, these attempts have often been based on the correction of end-state postures rather than online coordination between the different segments involved. Studies using vibratory stimulus to guide both forearm and upper arm movement simultaneously through the course of a gesture are less present in the scientific literature. Moreover, the results of those studies generally indicate that the positive effects of the vibrotactile system is negligible in gestures involving multiple degrees of freedom ([6,11]).

Invariably, one of the key barriers to the use of this technology is the user's ability to interpret multiple tactile cues, particularly when they are presented simultaneously. In effect, subject ability to attend to multiple distinct vibrotactile signals may be associated with both physiological (e.g. masking phenomena associated with mutually inhibitory pathways) [12], as well as higher order cognitive processing capacity [13,14]. For vibrotactile technology to be effective in more complex motor learning tasks, further work is required to determine specific configurations which favor one's ability to perceive and respond to multiple vibratory stimuli. In the present paper, our aim is to explore how stimulation parameters influence subject perception of vibrotactile patterns applied to the forearm and upper arm. More specifically, we examined the effects of (1) sequential versus simultaneous vibrotactile stimulation; (2) the temporal structure of vibrotactile stimulus upon subject perception; and (3) differences in pattern recognition between the two segments. During the experimental task, subjects were required to compare two vibrotactile sequences with varying levels of synchrony (i.e. temporal patterning between bursts of vibratory stimulus).

# 2 Materials and Methods

## 2.1 Participants

Sixteen healthy adult participants (7 males) with an average age of 24 years (SD = 2 years, range = 20–27 years) and no known neurological or orthopedic conditions were recruited for this study. All had either normal or corrected vision.

## 2.2 Experimental Setup

Vibrotactile stimuli were generated using a customized system comprised of a control unit and two vibratory modules each consisting of twenty-four vibrating actuators arranged in an 8x3 matrix (MTX-Lab, Caylar, France). Each vibrating actuator was a rotating eccentric mass encapsulated in a cylindrical tube with a 5 mm diameter and 11 mm length. Vibrators were spaced 10 mm from center to center and were fixed into a silicon support, holding them perpendicular to the surface of the skin. Surface contact between each vibrator and the underlying skin was thus 19.6 mm$^2$. Only 6 adjacent vibrators of each module (3x2 matrix at the center of the module) were activated (see Figure 1.1).

The two vibratory modules were placed on the left arm of each participant with Velcro straps (see Figure 1.2). Each was applied lengthwise along the ventral surface of the arm, with one at the level of the forearm and the other at the level of the upper arm. Participants were seated at a desk. The left arm was placed in a comfortable position before them, the shoulder flexed and slightly abducted, with the hand resting along a raised horizontal surface. A computer was then placed on the desk in front of the participant such that they read instructions on the screen whilst using their keyboard with their right hand to provide responses. This computer piloted the tactile device via ethernet connection and delivered visual instructions to the screen. The participants also wore headphones to render vibrating actuators inaudible during the experiment.

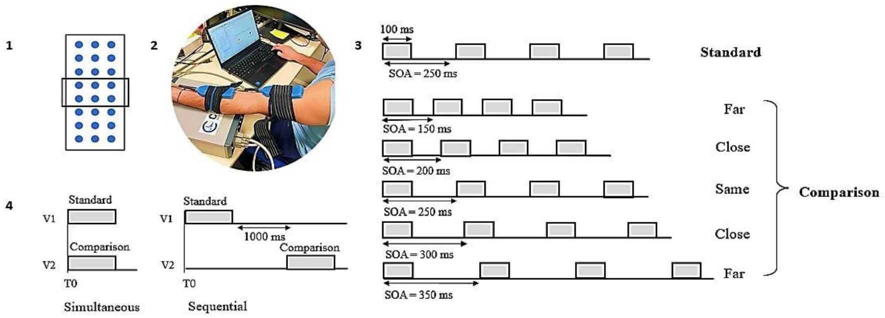

**Fig.1.** 1. Vibrators activated during experiment. 2. Experimental Setup. 3. Standard and comparison sequences. 4. Simultaneous and sequential presentation.

## 2.3 Experimental procedure

The experimental task required participants to indicate whether the temporal patterning of the stimuli applied to the forearm and upper arm were the same or different. Vibrotactile sequences consisting of 4 or 6 100 ms vibratory bursts (250 Hz) punctuated by specific stimulus onset asynchronies (SOA) were presented. One of the two vibratory sequences, the standard sequence, had a constant SOA of 250 ms. The other vibratory sequence, the comparison sequence, had a varying SOA, ranging between 150 ms and 350 ms (i.e. 150 ms, 200 ms, 250 ms, 300 ms, 350 ms). Therefore, the comparison sequence was composed of either the same temporal patterning as the standard, or a different temporal patterning, that is, with shorter or longer SOA. Also, the difference in temporal patterning between the standard and the comparison could be classified as either far (SOA of 150 ms or 350 ms) or close (SOA of 200 ms or 300 ms).

To prevent response strategies whereby participants might attend primarily to the number of vibratory bursts, or to the total duration of the sequence, the number of bursts (4 or 6) changed between sequences. According to the number of bursts and the SOA, the total duration of the sequences varied between 600 ms and 2100 ms (see Figure 1.3). The standard and comparison sequences were presented using two different modes: (1) simultaneous presentation, during which both vibrotactile sequences were presented at the same time; and (2) sequential presentation, during which the two vibrotactile sequences were presented one after the other, separated by a 1 s delay (see Figure 1.4). In this experimental protocol, the standard vibrotactile sequence was always presented first. However, the standard sequence was presented on the forearm or the upper arm, depending upon the experimental block.

During the experimental procedure, visual instructions were provided via the computer screen. Following each trial, participants were prompted to indicate whether the paired vibratory sequences were "the same" or "different" using the associated colored buttons on the keyboard. A time limit of 4 s was imposed for providing responses.

Each participant completed the experimental task for both presentation modes (simultaneous, sequential) and for both positions of the standard vibratory sequence (forearm, upper arm), corresponding to a total of four experimental blocks. The order of the experimental blocks was counterbalanced across participants. Within each experimental block, comparison sequences with SOA different from the standard (i.e. 150 ms, 200 ms, 300 ms, 350 ms) were presented 4 times each. Comparison sequences with the same SOA as the standard (i.e. 250 ms) were presented 8 times. In this way, 8 of the 24 trials in each block comprised two sequences with identical temporal patterning, 8 trials comprised sequences with a shorter temporal patterning than the standard, and 8 trials comprised comparison sequences with a longer temporal patterning than the standard.

### 2.4 Statistical Analysis

Percentage of correct responses was computed for each participant and each condition. Repeated-measures analysis of variance (ANOVA) was carried out, with Presentation mode (sequential, simultaneous), Comparison sequence SOA (150 ms, 200 ms, 250 ms, 300 ms, 350 ms), and Position of the standard sequence (forearm, upper arm), as within participant factors.

## 3 Results

Overall, participants correctly perceived whether the two vibrotactile sequences applied to their upper limb were the same or different in 75.5% (SD = 12.9) of the trials. The rate of correct responses was significantly greater for sequential presentation (81.9%, SD = 14.2) than for simultaneous presentation (69.1%, SD = 8.5) (*F* (1,15) =

10.90, $p < .01$, $\eta_p^2 = .42$). The position of the standard vibrotactile sequence did not have a significant effect upon perception ($F$ (1,15) < 1, $p = .68$, NS), with a correct response rate of 74.9% and 76.0% for the forearm and upper arm respectively.

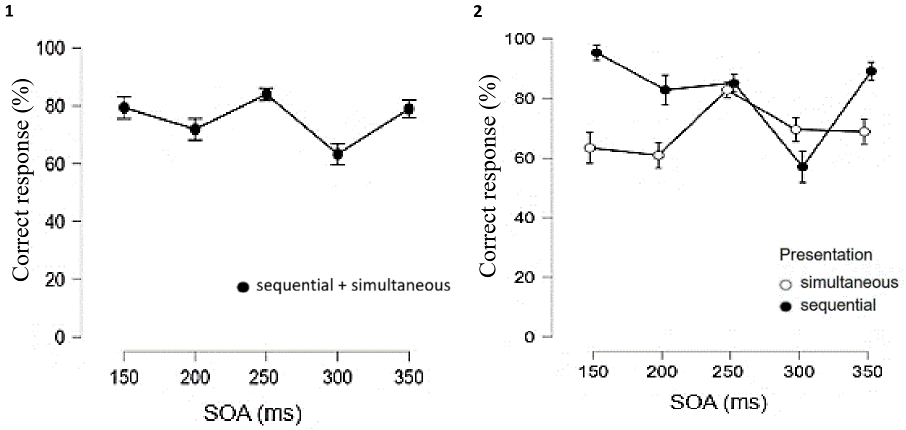

**Fig.2.** 1. Percentage of correct answers according to varying stimulus onset asynchrony (SOA). 2. Percentage of correct responses according to SOA for the simultaneous and sequential presentation of vibratory stimulus (error bars represent standard error).

There was a significant effect of SOA ($F$ (4,60) = 12.83, $p < .001$, $\eta_p^2 = .46$) showing an advantage of far over close SOA ($p < .001$) and an advantage of same over close SOA ($p < .01$; see Figure 2.1). Finally, there was also a significant interaction between Presentation and SOA ($F$ (4,60) = 7.39, $p < .001$, $\eta_p^2 = .33$) (see Figure 2.2). This interaction showed two different patterns of the effect of SOA, according to the mode of Presentation. In the sequential presentation, there was an advantage of far over close SOA ($p < .001$) and an advantage of same over close SOA. However, in the simultaneous presentation, there was a global advantage of the same SOA over all different SOA ($p < .001$) but no advantage of far over close SOA.

## 4 Discussion

The aim of this study was to examine how stimulation parameters influence subject perception of vibrotactile patterns. Using an experimental protocol, participants were required to indicate whether the temporal patterning of the stimuli applied to the forearm and upper arm were the same or different. The results of this experiment indicated that (1) perception was more accurate when the two signals were presented one after the other than simultaneously; (2) temporal patterning strongly influenced the accuracy of responses and (3) placement of the standard sequence on either the forearm or upper arm had no effect on task performance. Here we discuss how these findings may assist in the design of assistive technologies which incorporate multiple vibrotactile signals in shaping movement responses.

Effectively configuring stimulation parameters for wearable vibrotactile devices represents an important challenge when using these types of devices to influence complex behaviors. The results of the present study indicate that user ability to perceive specific patterns of vibrotactile stimulation is generally superior when presented in a sequential, rather than simultaneous manner. This observation appears consistent with recent studies where subjects compared the intensity of a standard vibratory stimulus to comparison stimuli [15] or compared vibratory patterns reproducing Braille alphabet [16]. Superior performance when distinguishing sequentially presented vibratory stimuli is likely attributable to the ability to represent differences between the tactile stimuli in the somatosensory cortex, and to leverage working memory in the prefrontal cortex [15,17]. Conversely, simultaneously vibratory stimulation implies concurrent transmission and may induce stimulus integration. As such, the use of simultaneous vibratory signals would thus be generally susceptible to interelement masking at lower levels of the perceptual system [18]. In the present study, these effects upon the ability to distinguish the two signals were observed regardless of whether the standard vibratory stimulus was placed on the forearm or upper arm, revealing no asymmetrical masking between the two segments.

Differences in the temporal structure of the vibratory patterns revealed interesting effects upon subject ability to distinguish signals across the sequential and simultaneous conditions. In the sequential presentation of vibratory stimuli, we found a rather classic effect [19], where participant ability to distinguish two signals was greater when faced with markedly different temporal patterns (i.e. far SOA sequences) as opposed to minor temporal differences (i.e. close SOA sequences), and with equally reliable perception when faced with identical temporal patterns. The specific decrease in the accuracy of responses for the 300 ms SOA in the sequential presentation condition is somewhat more difficult to account for. Certain studies have previously suggested the possibility of SOA specific effects in the decay of short-term tactile representations [20]. It may be the case that neural time courses involved in encoding and recall of haptic memory contribute to a specific instance where these two patterns are not easily individuated [21].

On the other hand, when presented simultaneously, participants perceived the condition in which the signals comprised identical temporal patterning significantly better than in situations with mixed temporal patterning. This may be due, in part, to the use of a distinct perceptual strategy. In this situation, the synchronous nature of the vibrations may lead subjects to perceive the stimuli as a unified sensation, rather than as two separate vibrotactile signals. In this manner, participants would attach less importance to the specific temporal structure per se [18]. Taken together, these findings indicate firstly that the level of differentiation between multiple vibrotactile signals must be high for them to be clearly perceived and interpreted when using sequential vibratory feedback; and secondly, that the use of synchronized patterns may be particularly salient for vibrotactile devices which transmit feedback online across multiple segments.

The performance differences observed between the perception of vibrotactile signals in the sequential and simultaneous conditions may provide insight into the use of paired vibratory stimuli in motor learning. For example, it may be pertinent to select the feedback mode according to the movement task. In ballistic movements (e.g. golf swing), the duration of the gesture and the associated motor planning does not lend itself to real-time, simultaneous feedback. Sequential feedback might, however, be harnessed immediately following the gesture to provide information regarding task performance. This might potentially include distinct vibrotactile signals indicating timing or coordination errors [5,22]. Based upon our results, it would also be advisable to exploit patterns with marked temporal asynchrony to strongly convey the desired message. Conversely, more deliberate actions (e.g. handwriting) which imply greater movement durations could benefit from feedback through the course of the gesture. As indicated above, the key to this type of feedback modality might be exploiting highly synchronous stimulation. In this type of configuration, the resonant property of the paired vibrotactile stimulus might be used to signal compliance with the desired coordination between the two segments (i.e. forearm, upper arm), as opposed to cueing each segment independently.

Following this study, several important questions regarding the perception of multiple vibratory stimuli remain unanswered. As indicated above, it is difficult to determine the exact cognitive and perceptual mechanisms associated with the performance discrepancies observed in the experiments carried out here. The use of specific perceptual strategies when faced with varying patterns of vibrotactile stimuli has been previously suggested in the literature [21]. It might therefore be pertinent to further investigate potential strategies using experimental and/or phenomenological methods. For example, this might involve evaluating discrimination capacities when faced with different degrees of vibrotactile synchrony (i.e. regular vs. chaotic). It should also be recognized that the present study manipulated temporal patterning of feedback signals by varying delays between the bursts of vibrotactile stimulus. Future experiments might also exploit burst time parameters to accentuate potential differences between signals, and thereby render them more perceptible to the user. Finally, perception of the vibrotactile signals here was limited to static postures. It remains to be seen whether response rates would be comparable through the course of movements where there is a continuous flux of tactile and proprioceptive afferents associated with segmental displacement and physical contact with the surrounding environment.

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