Studying the Perception of Vibrotactile Haptic Cues on the Finger, Hand and Forearm for Representing Microgestures

Suliac Lavenant[*]
Univ. Lille, Inria, CNRS,
Centrale Lille, UMR 9189
CRIStAL

Alix Goguey[†]
Univ. Grenoble Alpes,
CNRS, Grenoble INP, LIG

Sylvain Malacria[‡]
Univ. Lille, Inria, CNRS,
Centrale Lille, UMR 9189
CRIStAL

Laurence Nigay[§]
Univ. Grenoble Alpes,
CNRS, Grenoble INP, LIG

Thomas Pietrzak[¶]
Univ. Lille, CNRS, Inria,
Centrale Lille, UMR 9189
CRIStAL

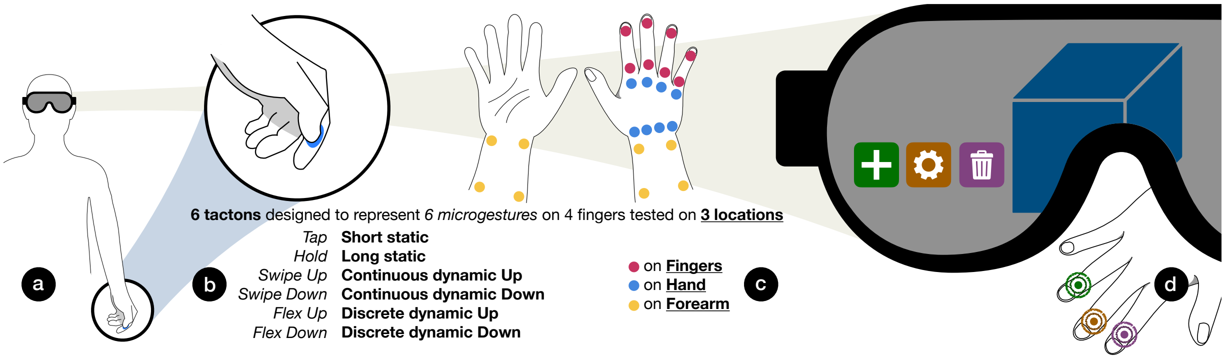

Figure 1: Vibrotactile Haptic Cues for representing microgestures : a) an example of microgesture interaction in mixed reality; b) 6 tactons designed to represent 6 microgestures; c) the 6 tactons are tested on 4 fingers with 3 haptic device locations; d) an example of vibrotactile feedforward for microgesture interaction in mixed reality.

Abstract

We explore the use of vibrotactile haptic cues for representing microgestures. We built a four-axes haptic device for providing vibrotactile cues mapped to all four fingers. We also designed six patterns, inspired by six most commonly studied microgestures. The patterns can be played independently on each axis of the device. We ran an experiment with 36 participants testing three different device locations (fingers, back of the hand, and forearm) for pattern and axis recognition. For all three device locations, participants interpreted the patterns with similar accuracy. We also found that they were better at distinguishing the axes when the device is placed on the fingers. Hand and Forearm device locations remain suitable alternatives but involve a greater trade-off between recognition rate and expressiveness. We report the recognition rates obtained for the different patterns, axes and their combinations per device location. These results per device location are important, as constraints of various kinds, such as hardware, context of use and user activities, influence device location. We discuss this choice of device location by improving literature microgesture-based scenarios with haptic feedback or feedforward.

Index Terms: Vibrotactile cues, microgestures, haptic vocabulary.

1 Introduction

Microgestures are subtle movements that can be used to interact with a system. In this paper, we focus on *hand microgestures* such as moving the thumb on other fingers of the same hand [14], or performing a flexion or extension of a finger in the air [13]. They are fast to perform, and independent of the wrist and arm motions and orientations, allowing for less exhausting interactions than other types of gestures [13]. They can also be executed eyes-free (i.e. without looking at the hand) and while performing a primary task (e.g. driving) [53, 56]. For these reasons, research on microgesture has been very active, with a strong focus on sensing and recognizing techniques [32, 35, 37, 49, 52, 57].

However, accurate sensing techniques represent only one challenge for the design and implementation of microgesture interaction. To become mainstream, microgesture interaction must provide to the users an accurate response to their actions (*feedback*) and information about possible actions and their resulting effects (*feedforward*) [18]. In interactive systems, feedback and feedforward are typically conveyed *visually*. When it comes to microgesture interaction, few studies have focused on how feedback and feedforward information could be provided. Unsurprisingly, the only exceptions, investigated *visual* representations exclusively, either to assist users in figuring out which microgestures can be performed [23, 34] or what graphical notation to use [11, 12].

Yet, there are many situations for which microgesture interaction is promising and being studied, but for which the visual channel is not available. A typical situation is that of people with visual impairment (PVI), people who in their daily life simply cannot rely on sight and mostly use non-visual interaction modalities [22, 21]. For instance, for the case of text selection by PVI performing microgestures [22], feedback and feedforward is only provided through audio. Other situations are defined by activities such as running. In these situations, users usually rely on a smartwatch for feedback,

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[*] e-mail: suliac.lavenant@inria.fr
[†] e-mail: alix.goguey@univ-grenoble-alpes.fr
[‡] e-mail: sylvain.malacria@inria.fr
[§] e-mail: laurence.nigay@univ-grenoble-alpes.fr
[¶] e-mail: thomas.pietrzak@univ-lille.fr

with their smartphone either in their pocket or strapped to their arm [5]. This setup means that touch screens are either small or hard to reach, making it difficult to access visual information when on the move. Similarly, microgestures hold great promise for activities such as driving [42], where staying focused on the road is crucial. As with running, it can be very dangerous to divert attention to visual tasks while driving. Finally, interaction using microgestures coupled with gaze is promising for mixed reality [13], in order to avoid gestures in the air, which can be exhausting during extended usage.

In the above-mentioned situations of microgesture interaction, feedback and feedforward must be provided through a non-visual channel. Furthermore, the only existing studies on lexical feedback and feedforward (actions) [1] for microgesture interaction studied visual [11, 34] solutions. The audio channel is a possible solution as in [22]. But that channel on its own suffers from limitations. For PVI, interaction already heavily relies on audio, and audio processing can be long and tedious (Recommendations D in [17]). Audio may also be limited in noisy environments. Moreover, while running or driving a car, it is essential to remain aware of the environment, which can make audio feedback unsuitable. Because of this, wearing headphones while cycling or running is illegal in the traffic in several countries and in some running races[1]. Finally, it is hard to process sound while performing a main task at the same time [39].

Considering these constraints, haptic, and specifically through the use of vibrotactile cues, is very promising for providing feedback and feedforward in these situations. But since vibrotactile cues have never been used to represent microgestures, we must first study how to represent them. Much remains to be done to understand how such vibrotactile information could be effectively delivered given the large number of tactile cues parameters [6]. Notably, vibrotactile cues are perceived through the skin, the body's largest organ, raising the question of *where on the body such cues should be provided for microgesture interaction*. Given that microgestures are performed on the fingers, fingers and hand are the first options to consider when it comes to providing vibrotactile cues. Wearable and haptic devices are frequently placed on the fingers and hand, which can make these locations even more suitable. In addition, many wearables and haptic devices are worn on the forearm making this location, even though somewhat more distant from the finger, a suitable distal location [27, 50]. Moreover, forearm equipment is more discreet than hand equipment, making this solution particularly relevant for PVI users who prefer to avoid the social stigma associated with assistive technology usage [9].

In this paper, we investigate how to represent microgestures with vibrotactile patterns (tactons [6]). We focus on 6 tactons (including some using tactile animation illusions such as the funneling illusion [2, 26]) that could be used to convey 6 frequent microgestures (*Tap*, *Hold*, *Flex Up*, *Flex Down*, *Swipe Up*, *Swipe Down*), alongside four axes, one corresponding to each finger (from index to little). We test how accurately users recognize these patterns when performed at three different locations (fingers, back of the hand, and forearm). Our results suggest that the location on fingers has the greatest potential for transmitting tactons and in particular for axis recognition. According to our results, the second-best location is on the forearm, which achieves better results than the hand location for axis recognition. Based on these results, we illustrate how such tactons provided on fingers or on forearm could enrich microgesture interaction.

Our work provides the following contributions: 1) Definition of six different tactons that can be used to enrich microgesture interaction; 2) Implementation of a haptic prototype with four axes, one per finger, to transmit the tested tactons; 3) Empirical evidence of tacton recognition rate by users in three different stimulation locations; 4) Scenarios in which tactons would enrich microgesture interaction, under different conditions (location of the device and how it is used for feedback or feedforward).

2 RELATED WORK

Two factors are important for the design of haptic feedforward and feedback for microgestures. The first one is the location of stimulation. There is a trade-off to consider between keeping the fingers and hands free and providing an accurate gesture interpretation by users. The second factor is the design of a recognizable tactile vocabulary, with an appropriate choice of parameters and values.

2.1 Actuator Location

Vibrotactile haptic devices have been tested at various locations on the body such as the feet, fingers, waist, legs, chest, back and arm [19]. The fingers are indeed an obvious location given our focus on microgesture interaction and the high sensitivity of fingers [55]. However, we also want to explore other device location possibilities as they offer interesting alternatives for hands-free applications [28]. As a first step, we chose to explore locations on the hand and the forearm.

Fingers Using one actuator per finger is a common approach [20, 54], but it lacks expressivity. It is possible to increase the vocabulary with two actuators on each of the four fingers of a hand. Liu *et al.* evaluated the ability of users to identify the 255 possible combinations with this configuration [38]. They found that as the number of activated actuators increases, the recognition rate decreases, and the reaction time becomes longer. Other approaches use more complex devices such as vibrotactile arrays on a fingertip to render localized touch sensation of a 3D object [4]. The same kind of device can indeed be used to encode information with a larger vocabulary. In summary, there is a trade-off to consider between the expressiveness of the haptic vocabulary and the cumbersomeness of the device. In our context of tactile feedback for microgestures, our objective is to keep the fingers free to move.

Hands Actuators on the palm side of the hand is common for handheld devices [48]. However, actuators on the palm hand impede finger movements, tasks, and interaction. Therefore, we rather consider the back side of the hand. In the literature, it has rarely been studied with more than one actuator. To the best of our knowledge, only few papers used several actuators on the back side, with either 4 [58] or 10 actuators [25]. In both papers, the authors used the actuators to convey directions guiding users' hand for 3D or 2D exploration. Results show that users were able to recognize the different stimuli with one actuator at a time [25] or up to 2 actuators together [58]. Although not studied in depth, both papers show promising results which encourage us to test a richer haptic vocabulary using back hand-side actuators.

Forearms Different locations on the forearm for actuators have been studied. In their work, Cholewiak *et al.* [15] showed that a stimulation point close to a natural joint are easier to recognize. They also showed that increasing the space between actuators significantly improves localization of vibrations. Therefore, the actuators of the device should be placed close to joints and sufficiently spaced from each other. Another point to consider is that vibrations are better localized across the width of the forearm than along its length [43, 45]. Many devices transmitting vibrotactile information via the forearm have been developed [6, 20]. They rely on several parameters such as location, rhythm, and roughness to encode information. To the best of our knowledge, the only instance of haptic feedback mapping information from fingers to the forearm used force feedback with a limited set of parameters for three fingers [40]. In our work, we use several vibrotactile parameters to provide a richer vocabulary.

Although many body locations for vibrotactile actuators have been studied [19], in this section we identified three locations that

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[1] https://bikepush.com/cycling-with-headphones

could be suited to transmit vibrotactile information mapped to four fingers. These three locations have already been compared to provide distal vibrotactile feedback in virtual environments [50]. However, they have not been studied to represent microgestures. In our experiment below we study their advantages and drawbacks.

2.2 Tacton Parameters

Tactons are tactile icons which encode information by varying signal parameters such as the amplitude, frequency, duration, location, and rhythm of a vibration [2, 3, 6, 30, 51]. A frequent strategy to encode information is to use a repeating pattern of short vibrations [10, 36]. Using this strategy, we can encode different pieces of information by varying the number of short vibrations in a sequence. Although simple and straightforward, this strategy quickly breaks down when the information vocabulary to encode increases: a large vocabulary will lead to potentially long sequences that are hard to track. To increase tacton expressiveness, researchers are exploring different signal parameters.

Parameters that are commonly studied to increase vocabulary are amplitude and frequency [3, 6, 30]. Varying the amplitude enables to use different levels of vibration *intensity*, while varying the frequency enables to use different levels of vibration *roughness*. Another common parameter is the duration of the vibration signal [3] allowing a continuous range from short to longer vibrotactile icons enabling simple discrimination.

Another approach is to use rhythms, which drastically increase the number of ways to encode information [10, 36]. However, it has two caveats: 1) longer the sequences cause recognition errors, and similarly 2) large vocabularies are hard to remember. Ternes and MacLean studied these trade-offs and recommended encoding information with duration and irregular cues [51].

A different approach is to increase the number of actuators. For instance, Oakley *et al.* [43] designed a 3×3 array therefore conveying 9 different patterns. More complex scenarios can also be envisioned, such as transmitting a letter through the activation of multiple actuators at the same time [47]. One can even go further using both a combination of multiple actuators and previously described signal parameters, such as frequency. Location could convey directional information while frequency could convey the distance to an obstacle [16]. Finally, placing actuators in an array can also be considered as a tactile display enabling the use of vibrotactile animations conveying directions for instance [45].

The use vibrotactile illusions, such as the funneling effect [2], can also increase the vocabulary. This effect interpolates the amplitude of the signal of two actuators to give the illusion of a phantom vibration point in-between. Tactile animation illusions such as saltation effect [24] and Apparent Haptic Motion (AHM) [8] use discrete signals to create an illusion of a vibration moving between several points. The saltation effect uses repeated vibrations while AHM uses sequential activations with overlaps.

Previous works on vibrotactile cues show a large panel of actionable parameters. In this paper, we chose to investigate a diversity of cues, both in terms of locations and patterns, with static and dynamic ones.

3 EXPERIMENTAL FACTORS

We designed a haptic vocabulary with the objective to render both *static* and *dynamic* patterns on each of the four fingers of a hand. On the one hand, static cues could be used to deliver feedforward or feedback for discrete microgestures like a *tap* or a *hold*. On the other hand, dynamic cues could provide progress information or represent continuous microgestures like *flexing* or *swiping* a finger.

3.1 Tactons

We encode information with Tactons along two dimensions. The first dimension is the *axis* associated with each finger. Our mapping uses pairs of actuators to define these axes. They provide animation rendering of various tactile illusions such as the funneling effect [2, 26]. The second dimension of our Tactons is the *pattern*. In this study, we propose two static and two dynamic patterns to represent two different kinds of information. Figure 2 illustrates the four patterns. The parameters of these patterns such as frequency, amplitude and duration were adjusted through informal pilot tests. One of the key aspects was to make the two static patterns and the two dynamic patterns distinguishable.

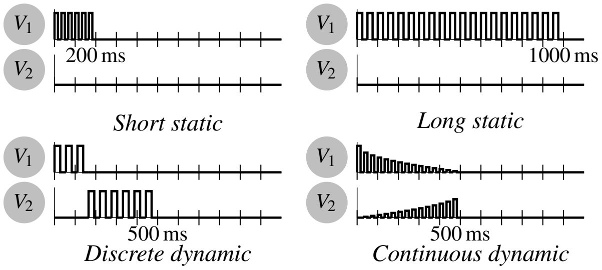


Figure 2: The four vibration patterns: short static, long static, discrete dynamic and continuous dynamic. V_1 and V_2 represent the two actuators of a given axis. The two dynamic patterns can be played in both directions by inverting V_1 and V_2, since their respective microgestures (Flex and Swipe) can be performed in both directions.

Short static The *Short static* pattern (SS) is a 200 ms vibration with a 250 Hz frequency on the given axis, and a constant vibrational amplitude corresponding to the maximum value of the actuator. It could typically be used to represent taps of the thumb on one finger. This pattern can be played either on one of the actuators or in-between with the funneling effect, but we only experiment one position in this study.

Long static The *Long static* pattern (LS) is a variation of *Short static*, with a longer duration of 1000 ms and a 100 Hz frequency, and a constant vibrational amplitude corresponding to the maximum value of the actuator. This pattern could be used to represent a hold microgesture, like dwell-based interactions.

Discrete dynamic The *Discrete dynamic* pattern (DD) actuates the two actuators of an axis in a sequence to represent a direction movement. After informal pilot tests, we use a longer end vibration to accentuate the movement direction: $\frac{1}{3}$ of the vibration time is at the start actuator and the $\frac{2}{3}$ others at the end actuator. The pattern duration is 500 ms in total with a 100 Hz frequency, and a constant vibrational amplitude corresponding to the maximum value of the actuator. The animation can be played in both directions, hence encoding the two directions of a microgesture such as flexing a finger.

Continuous dynamic The *Continuous dynamic* pattern (CD) uses a square root funneling effect to give the sensation of a vibration moving smoothly along the axis. The pattern has a duration of 500 ms with a frequency of 250 Hz, and an amplitude set to the maximum value of the actuator. But the individual amplitude of each actuator depends on the position of the vibration as defined by the square root funneling effect [31]. It can also move in both directions, to represent a swiping microgesture of the thumb on a finger.

3.2 Location

Our objective is to provide feedforward and feedback information for microgestures. We discuss below the advantages and drawbacks of three body locations: the fingers, the hand, and the forearm. Figure 3 shows the positions of the actuators for the three body locations.

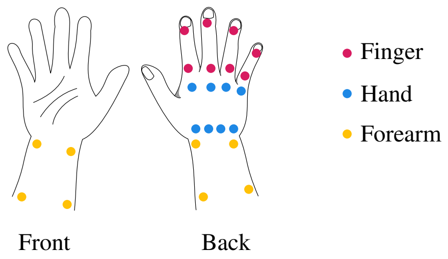


Figure 3: Actuators location of the three prototype locations.

Fingers The obvious position to provide haptic feedback related to fingers is on the fingers themselves. We placed the actuators on the distal phalanx and the proximal phalanx of the back of each finger as shown in Figure 3, in red.

Hand Some situations may require keeping the fingers and palm free. For instance, to let the users freely touch or even grasp physical objects. Although finger actuators positions allow finger movement, they will never allow complete freedom of movement. Additionally, some physical constraints imposed by other devices may prevent the use of the finger locations. To keep the users' fingers free, we propose to align the actuators with the metacarpal bones on the dorsal side of the hand. For each finger, we placed one actuator close to the fingers, and one close to the wrist as shown in Figure 3, in blue.

Forearm Space constraints due to other devices, or casual contexts, may completely restrict the use of actuators on the finger or hand. In such cases, the forearm could offer a suitable alternative. The fingers and hand have evident areas for actuators positioning. On the opposite, the forearm does not have intuitive placement for 4 axes. The placement includes two parameters: positioning of the axes around the forearm and distance between two actuators of an axis. At the design stage, we conducted informal pilot studies to explore different configurations. Similarly to the literature, we have found that locating the actuators too close across the width of the forearm leads to poor discrimination [43, 45]. Four axes side by side, below or above the forearm, have a bad recognition and a neighbor axis confusion. In contrast, having all four axes equidistant provides a better axis discrimination. Then, still in agreement with previous research, we found that actuators too close together along the length of the forearm led to actuators confusion. We chose a distance that was not too long, but long enough to allow good discrimination. For each axis we placed one actuator close to the wrist joint, and one 8 cm down on the forearm as shown in Figure 3, in yellow.

3.3 Hypothesis

Our motivation is to be able to represent 4 types of microgestures on 4 fingers, but we anticipate that the perception will be affected by the device location. For example, previous research showed that the human body better recognizes stimuli near natural joints [15]. Therefore, we expect better overall recognition at the Finger location, considering the multiple joints present in each finger and the direct mapping between axes and fingers. For the same reason, we expect better recognition with Hand than with Forearm. Therefore, we hypothesize that (H1) participants will identify Tactons more easily on the Finger than on the Hand, and more easily on the Hand than on the Forearm. Other research showed that tactile animations across the width of the forearm are easier to recognize than tactile animations moving along its length [43, 45]. Therefore, we hypothesize that (H2) participants will more easily recognize Axes than Patterns on the Forearm.

4 Methodology

We ran a user study to know if users can discriminate between different Tactons (Patterns × Axes), and to study the potential effect of the device location.

4.1 Procedure

We first described to the participants the experiment and its structure with three phases: demonstration, experiment and debrief. Then, we showed them the device and described the concepts of locations, axes, and patterns. Finally, before starting the experiment, we equipped participants with the haptic device and a noise-canceling headset.

In the *demonstration phase*, each pattern was shown to the participant, in the same order repeated 8 times. The participants were asked to draw or describe their perception of each pattern on a paper sheet on which six hands were drawn, each with a printed number on it. We used this procedure to avoid giving participants any clue with our own names and notations. The hand and numbers already printed on the sheets were meant to speed up the notation process. Participants were encouraged to refine their notes at each repetition, to ensure they mapped each drawing/description to one pattern and that they were able to discriminate each pattern. To help participants familiarize themselves with the concept of axis, we played a 2000 ms funneling animation between the front and the back actuator 4 times on each axis.

We then moved to the *experiment phase*. In each trial, the device played a tacton encoding both a Pattern and an Axis. The participants had to guess the Axis and the Pattern, and were encouraged to leverage their notes for this. To record their answer, participants had to select the Axis with the left and right directional arrows. The Pattern must also be selected, on the same page as the axes, with the keyboard numeric keypad. After completing a trial, they had to press the enter key when they were ready to move on to the next trial.

Finally, we ended the session with a *debrief phase*, in which we asked demographics questions to participants, asked them to comment on the experiment, then discussed and answered any additional comments and/or questions they had.

4.2 Apparatus and Participants

Apparatus We used eight *HiWave HIHX9C005-8* voice coil actuators [29], attached with a scratch strip for precise and strong clamping. Each actuator was surrounded by foam to distribute the pressure between the skin and the actuator and isolate the vibrations. They were controlled with a Teensy 4.1 board connected to a custom board that modulates a frequency and an amplitude signal and performs a field-effect transistor (FET) amplification, similarly to [48]. Both signals were square shape generated with hardware timers. The frequency signal had a 50 % duty cycle. The amplitude signal used a high frequency signal (31 kHz) with an adjustable duty cycle that controls the resulting amplitude. The device communicated with the host PC with USB with raw HID. Figure 4 shows the apparatus. The experimental application was developed and running in Unity. The application and experimentation were carried out under the Windows 10 operating system.

Participants We recruited 36 participants at the local University and labs. Their age ranged from 18 to 45 years old (mean=24.41, std=5.80). 29 of them declared themselves as men, 6 as women and 1 as non-binary. Genders are not perfectly balanced due to the bias of the local population of computer science students, which is a potential limitation of the study. It should be noted, however, that other studies have found no gender differences in vibrotactile perception [41, 46].

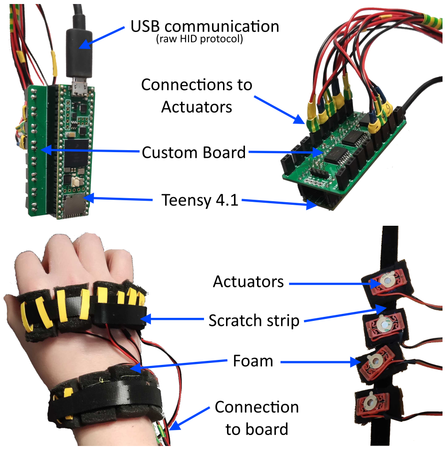


Figure 4: Apparatus used in the experiment. Left: Teensy 4.1 and custom boards. Right: actuators.

4.3 Experimental Design

Our experiment used a mixed design with PATTERN (*Short static*, *Long static*, *Continuous dynamic up*, *Continuous dynamic down*, *Discrete dynamic up*, *Discrete dynamic down*) and AXIS (Index, Middle, Ring and Little) as within-subjects factors, and DEVICE LOCATION (Finger, Hand and Forearm) as a between-subjects factor. We used a between-subjects design for our main independent variable, the DEVICE LOCATION factor, to avoid a learning effect. They are 12 PARTICIPANTS per location. Each participant performed 6 BLOCKS of each combination of PATTERN × AXIS. Participants experienced the same 6 BLOCKS but in a random order. In total, the experience lasted an average of 45 min. In total, we collected 12 PARTICIPANTS × 3 LOCATIONS × 6 BLOCKS × 6 PATTERNS × 4 AXIS = 5184 trials.

4.4 Data analysis

We performed the data processing and analysis with R and the `rstatix` package. We first analyzed the data with Anova to detect potential main effects and interactions. Mauchly's sphericity test was used. The adjustment was performed through, if necessary, the Greenhouse-Geisser method. In case of a main effect, the pairwise comparison was used for post-hoc analysis with the Bonferroni adjustment.

5 RESULTS

Figure 5 summarizes mean recognition success, with bootstrapped 95 % confidence intervals (CIs), for each device location (mean overall recognition rate, pattern recognition rate, and axis recognition rate). Figure 6 displays the confusion matrices of the patterns and Figure 7 of the axes for the three device locations.

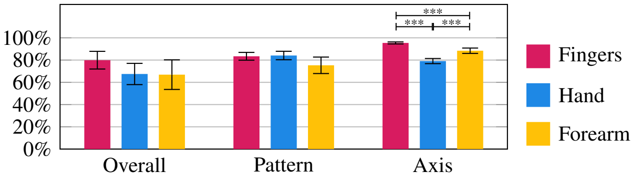
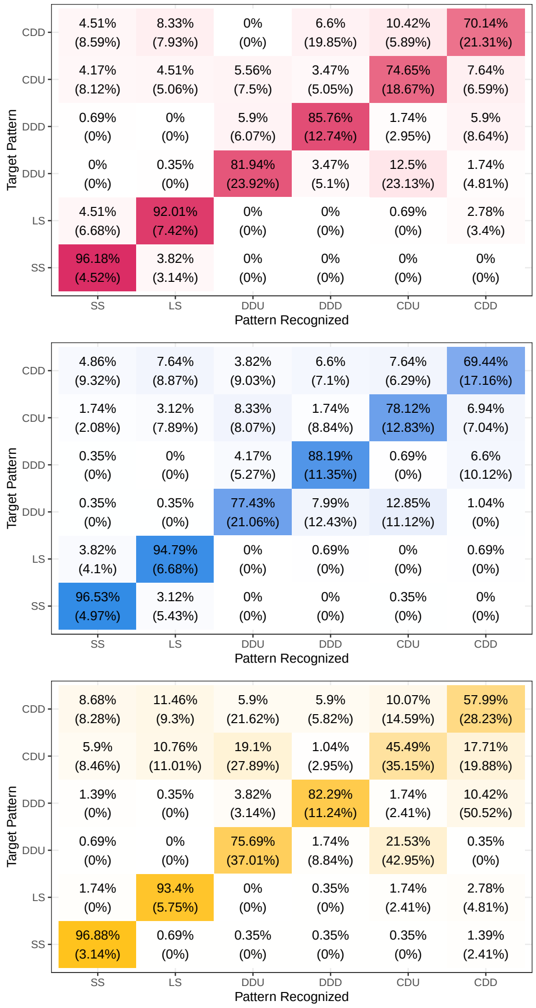


Figure 5: Recognition rate with 95 % bootstrapped CI per device location. "*" shows a significant difference.

An ANOVA analysis does not reveal a significant effect of LOCATION ($F_{2,33} = 2.328$, $p = 0.113$) on the overall recognition rate. However, an ANOVA reveals a main effect of PATTERN and AXIS (respectively $F_{3.43,113.23} = 21.619$, $p < 0.0001$ and $F_{2.69,88.61} = 2.966$, $p = 0.042$). Post-hoc pairwise analysis on patterns effect reveals a significant difference between every pattern pair but 3 (all $p < 0.0001$). The exceptions are between *Short static* and *Long static*, *Discrete dynamic up* and *Discrete dynamic down* and between *Continuous dynamic up* and *Continuous dynamic down*. Concerning the axis effect on general recognition, the post-hoc pairwise analysis reveals a significant difference between INDEX finger axis and LITTLE finger axis ($p = 0.000536$). For information, the mean and the CI of each location for overall recognition are as follows: FINGER location ($m = 79.9\%, CI = [71.8\%, 87.9\%]$), HAND location ($m = 67.5\%, CI = [58\%, 77.1\%]$) and FOREARM location ($m = 66.9\%, CI = [53.6\%, 80.2\%]$).



Target Pattern	SS	LS	DDU	DDD	CDU	CDD
CDD	4.51% (8.59%)	8.33% (7.93%)	0% (0%)	6.6% (19.85%)	10.42% (5.89%)	70.14% (21.31%)
CDU	4.17% (8.12%)	4.51% (5.06%)	5.56% (7.5%)	3.47% (5.05%)	74.65% (18.67%)	7.64% (6.59%)
DDD	0.69% (0%)	0% (0%)	5.9% (6.07%)	85.76% (12.74%)	1.74% (2.95%)	5.9% (8.64%)
DDU	0% (0%)	0.35% (0%)	81.94% (23.92%)	3.47% (5.1%)	12.5% (23.13%)	1.74% (4.81%)
LS	4.51% (6.68%)	92.01% (7.42%)	0% (0%)	0% (0%)	0.69% (0%)	2.78% (3.4%)
SS	96.18% (4.52%)	3.82% (3.14%)	0% (0%)	0% (0%)	0% (0%)	0% (0%)

Pattern Recognized

Target Pattern	SS	LS	DDU	DDD	CDU	CDD
CDD	4.86% (9.32%)	7.64% (8.87%)	3.82% (9.03%)	6.6% (7.1%)	7.64% (6.29%)	69.44% (17.16%)
CDU	1.74% (2.08%)	3.12% (7.89%)	8.33% (8.07%)	1.74% (8.84%)	78.12% (12.83%)	6.94% (7.04%)
DDD	0.35% (0%)	0% (0%)	4.17% (5.27%)	88.19% (11.35%)	0.69% (0%)	6.6% (10.12%)
DDU	0.35% (0%)	0.35% (0%)	77.43% (21.06%)	7.99% (12.43%)	12.85% (11.12%)	1.04% (0%)
LS	3.82% (4.1%)	94.79% (6.68%)	0% (0%)	0.69% (0%)	0% (0%)	0.69% (0%)
SS	96.53% (4.97%)	3.12% (5.43%)	0% (0%)	0% (0%)	0.35% (0%)	0% (0%)

Pattern Recognized

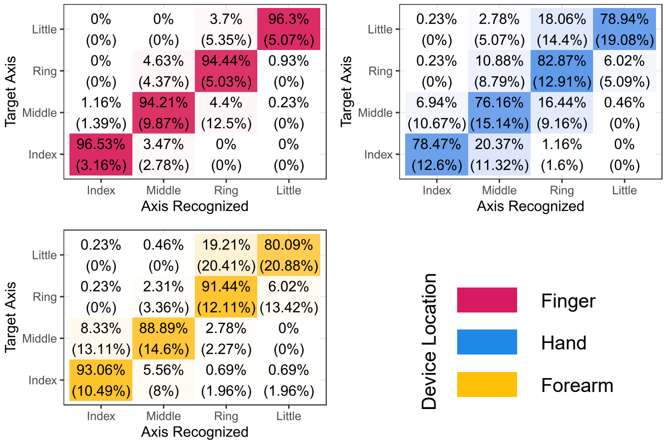
Target Pattern	SS	LS	DDU	DDD	CDU	CDD
CDD	8.68% (8.28%)	11.46% (9.3%)	5.9% (21.62%)	5.9% (5.82%)	10.07% (14.59%)	57.99% (28.23%)
CDU	5.9% (8.46%)	10.76% (11.01%)	19.1% (27.89%)	1.04% (2.95%)	45.49% (35.15%)	17.71% (19.88%)
DDD	1.39% (0%)	0.35% (0%)	3.82% (3.14%)	82.29% (11.24%)	1.74% (2.41%)	10.42% (50.52%)
DDU	0.69% (0%)	0% (0%)	75.69% (37.01%)	1.74% (8.84%)	21.53% (42.95%)	0.35% (0%)
LS	1.74% (0%)	93.4% (5.75%)	0% (0%)	0.35% (0%)	1.74% (2.41%)	2.78% (4.81%)
SS	96.88% (3.14%)	0.69% (0%)	0.35% (0%)	0.35% (0%)	0.35% (0%)	1.39% (2.41%)

Pattern Recognized

Figure 6: Pattern confusion matrices per device location with the recognition percentage and standard deviation in parentheses. (SS:Short Static, LS:Long Static, DD:Discrete Dynamic (U:Up, D:Down), CD:Continuous Dynamic (U:Up, D:Down))

For PATTERN recognition, the ANOVA analysis does not reveal any effect of LOCATION on pattern recognition rate ($F_{2,33} = 1.775$, $p = 0.185$). But, as could be expected, the ANOVA reveals a main effect of PATTERN on pattern recognition rate ($F_{3.37,111.12} = 23.478$, $p < 0.0001$). Post-hoc pairwise analysis on patterns effect reveals a significant difference between every pattern pair (all $p < 0.0001$) except between *Short static* and *Long static* and between *Continuous dynamic up* and *Continuous dynamic down*. For information, the mean and the

CI of each location for pattern recognition are as follows: Finger ($m=83.4\%, CI=[79.2\%, 87.7\%]$) and Hand ($m=84.1\%, CI=[80.2\%, 87.9\%]$) and Forearm ($m=75.3\%, CI=[67.9\%, 82.7\%]$). To explore any effect of device location on the recognition rate of each pattern, several ANOVAs were performed. Only *Continuous dynamic up* pattern shows a significant effect of device location on the recognition $F_{2,33}=6.615$, $p=0.004$. Post-hoc pairwise analysis reveals a significant difference between Finger and Forearm locations and between Hand and Forearm locations (all $p<0.0001$).



	Index	Middle	Ring	Little
Little	0% (0%)	0% (0%)	3.7% (5.35%)	96.3% (5.07%)
Ring	0% (0%)	4.63% (4.37%)	94.44% (5.03%)	0.93% (0%)
Middle	1.16% (1.39%)	94.21% (9.87%)	4.4% (12.5%)	0.23% (0%)
Index	96.53% (3.16%)	3.47% (2.78%)	0% (0%)	0% (0%)

	Index	Middle	Ring	Little
Little	0.23% (0%)	2.78% (5.07%)	18.06% (14.4%)	78.94% (19.08%)
Ring	0.23% (0%)	10.88% (8.79%)	82.87% (12.91%)	6.02% (5.09%)
Middle	6.94% (10.67%)	76.16% (15.14%)	16.44% (9.16%)	0.46% (0%)
Index	78.47% (12.6%)	20.37% (11.32%)	1.16% (1.6%)	0% (0%)

	Index	Middle	Ring	Little
Little	0.23% (0%)	0.46% (0%)	19.21% (20.41%)	80.09% (20.88%)
Ring	0.23% (0%)	2.31% (3.36%)	91.44% (12.11%)	6.02% (13.42%)
Middle	8.33% (13.11%)	88.89% (14.6%)	2.78% (2.27%)	0% (0%)
Index	93.06% (10.49%)	5.56% (8%)	0.69% (1.96%)	0.69% (1.96%)

Figure 7: Axis confusion matrices per device location with the recognition percentage and standard deviation (in parentheses).

For Axis recognition, an ANOVA analysis reveals a main effect of Location on axis recognition rate ($F_{2,33}=6.635$, $p=0.004$). Post-hoc pairwise analysis on device location effect reveals a significant difference between Finger location and Hand location, between Finger location and Forearm location and between Hand location and Forearm location (all $p<(0.0001)$). The Finger ($m=95.4\%, CI=[93.6\%, 97.2\%]$) location achieve better recognition rate than the Forearm ($m=88.4\%, CI=[83.9\%, 92.8\%]$) location, itself better than the Hand ($m=79.1\%, CI=[74.8\%, 83.4\%]$) location. An ANOVA does not reveal a significant effect of Axis on the axis recognition rate ($F_{2.12,69.86}=2.804$, $p=0.057$).

6 DISCUSSION

We studied the transmission of vibrotactile patterns mapped to fingers using three device locations. Our study shows that the participants can identify tactons more easily when the device is on their fingers. It also shows that *Short static* and *Long static* are better recognized than *Discrete dynamic*, and all three are better recognized than *Continuous dynamic*. Results also show that Patterns and Axes can be discriminated separately.

On another note, we can partially validate H1: the users achieve better recognition results for Finger location than the Hand. We note though that both locations have similar results for pattern recognition. The Finger location also gives better recognition by users than the Forearm. However, the results are significant only for axis recognition. We validate H2: the Forearm location gives better results for axis recognition than for pattern recognition.

All three locations have a recognition rate between 96 % and 97 % for the *Short static* pattern. The confusions of the *Short static* mainly occur with the *Long static*, for the Finger and Hand locations, or with the *Continuous dynamic down*, for the Forearm location. The *Long static* pattern provides a recognition rate between 92 % and 95 % for all three locations. For the Finger and Hand locations, the *Long static* pattern is mainly confused with the *Short static* pattern, but for the Forearm location, it is equally confused with the *Short static* pattern, *Continuous dynamic up* and *down* patterns. The other patterns have a recognition rate under 90 %, with the *Continuous dynamic* being the hardest to recognize for all three locations. Confusions can partially be explained by participants either getting the right direction but not the right vibration type, and *vice versa*. In addition, some participants indicated that they needed some time to get accustomed to the *Continuous dynamic* pattern.

Finally, Axes are better recognized with Finger. However, at all locations, confusions mainly come from adjacent axes, especially with the Hand and Forearm locations.

While placing the actuators on the fingers is best, device location possibilities may be bound to contextual constraints or users' preferences. For instance, users may not want to wear a glove all day. However, some devices can be taken advantage of, such as smartwatch wristbands which could accommodate forearm actuators, smart rings which could accommodate finger actuators, or other everyday worn jewelry that could be instrumented [44]. Similarly, some constraints may arise from already equipped devices, which may already have components preventing the placement of vibrotactile actuators at the optimum locations. For example, if one wants to use a microgesture sensing device equipped with bend sensors on the finger [54], they may need to consider the back of the hand or forearm to place vibrotactile actuators. If one wants to maintain a diversity of patterns but not axes, the hand location is the best solution. If one only wants 4 different patterns, both locations could be used if *Continuous dynamic* is removed from the pattern set. Given that confusions of *Discrete dynamic* are mostly with *Continuous dynamic* of the same direction, one could expect to achieve at least 90% of recognition. Reducing the number of axes and spacing them out more could also lead to recognition improvements. If one wants to maintain a diversity of axes but not patterns, the forearm is better suited. However, to maintain a diversity of both patterns and axes, designers will need to reduce the combinations. If such a trade-off can be made, both locations would fit.

Finger microgestures and tactons could also be relevant for people with visual impairment (PVI). Even though our study did not involve any PVI, research failed to find evidence of a difference on touch perception between PVI and sighted people [7]. Moreover, the visually impaired population is notoriously difficult to reach. Therefore, even if it is not optimal, the accepted practice is to first involve sighted people before involving PVI [7]. That being said, further studies are required to generalize our results with PVI.

One limitation is that we only study three locations: fingers, hand and forearm. Other locations could be found efficient (e.g. on the upper part of the arm or on the other parts of the body). In this paper, we chose to focus first on keeping a small distance between fingers and vibration points. Another limitation is that, with the forearm, patterns using two actuators are confusing (*Discrete dynamic* or *Continuous dynamic*). Future design of patterns for the forearm should take into account that the funneling effect on the forearm is fuzzier. Finally, we only tested vibrotactile signals on one axis at a time. Further investigations are required to confirm the recognition of patterns (whether of one kind, or several) on multiple axes at the same time. Investigating such scenarios is especially suited for microgestures which involve two or more fingers.

7 SCENARIOS

This section presents three scenarios inspired by the literature to illustrate envisioned uses of tactons for microgesture interaction. We discuss how tactons can be used as feedback or feedforward in several situations as presented in the introduction section, how techniques from the literature can be adapted, and at which location it would be best to perform the tactons depending on the context. These scenarios are ideas and examples of possible implementation, and do not constitute a contribution.

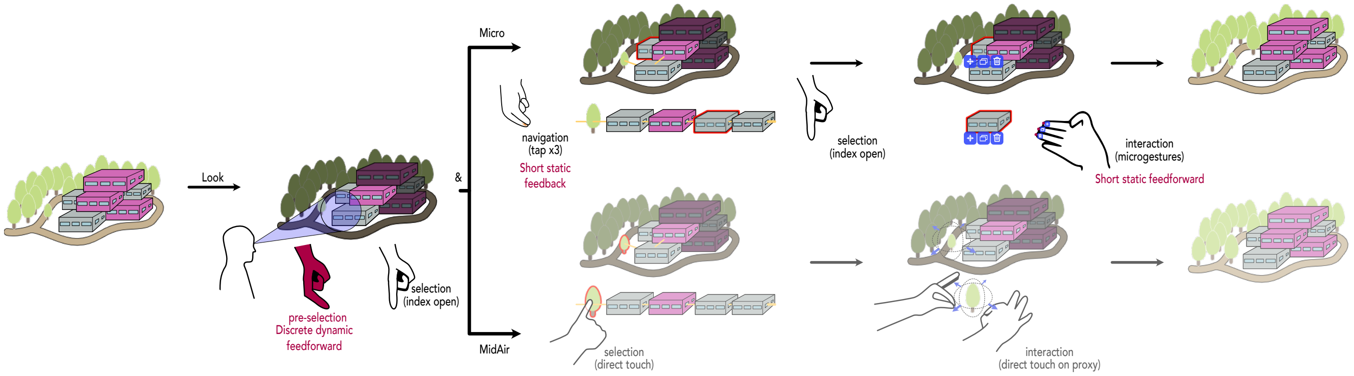


Figure 8: Integration of microgesture tactons into the Look&Micro 3D Selection technique (Courtesy of Chaffangeon-Caillet *et al.* [13] who kindly allowed us to re-use and modify the figure). Dark red elements were added to the original figure.

7.1 Text-selection with microgestures for People with Visual Impairment

As discussed in the introduction, microgestures constitute a promising interaction paradigm for people with visual impairment (PVI) [22, 21]. For instance, Faisandaz *et al.* have proposed μGeT [22], a text selection technique that extends touch interaction using microgestures. More precisely, users can *grab* the left (respectively right) handle of a text selection by performing an index (respectively middle) finger hold microgesture. A pinky tap microgesture resets the selection. Microgestures notably lack discoverability, especially for PVI who cannot rely on the few existing visual representations of microgestures [33]. For this reason, Faisandaz *et al.* had to teach the possible microgestures by manipulating participants' hands.

Tactons can be used to communicate these three microgestures to PVI. For instance, the index *Long static*, middle *Long static* and pinky *Short static* tactons can be played upon application startup as feedforward to inform users of the availability of these microgestures. Given the results of our experiment, the FINGER location would be best when it comes to distinguishing just two patterns on three different axes (index, middle and pinky fingers). However, to avoid the social stigma associated with assistive technologies [9], the FOREARM location would be more appropriate as it is more discreet, for example hidden under a long sleeve of clothing.

7.2 Microgestures for mobility scenarios

Microgestures have been acknowledged as particularly interesting for many scenarios where the user is on the move, with limited access to the usual input devices, such as while running in the streets [5] or driving a vehicle [42].

Boldu *et al.* [5] proposed Thumb-in-motion, a technique in which the tap and swipe microgestures, on one finger are detected by an interactive ring. The technique can be used to navigate in an application. The *Short static* tacton could be played when the users put on the ring for the first time, as feedforward to inform them that they can tap their finger to open the menu. When the menu is opened, a back-and-forth *Continuous dynamic* tacton could be played to indicate that in this context, the swipe up and down microgestures can be performed to navigate the menu. For this situation where only one finger is used, accurate recognition of the patterns should be the priority. Given that our study did not reveal an effect of location on pattern recognition, the tacton could be performed where the users prefer. Since the device proposed by Boldu *et al.* is a ring, the choice of the FINGER location would require minimal augmentation.

Driving a car is another situation where microgesture interaction is promising, and where vibrotactile feedback could be useful for maintaining the user's attention on the road, where there are many hazards. Typically, Neßelrath *et al.* [42] rely on finger extensions (flex microgestures) of both hands, while holding the steering wheel, to perform hierarchical navigation in menus: the number of extended fingers on the left hand specifies a menu, while extended finger on the right hand activates a car control. A combination of *Continuous dynamic* tactons could be played as feedback when the driver activates a command via the other car controls, for instance decreasing the temperature of the AC via the interactive dashboard. The tactons are used to inform the driver of the availability of microgestures as safer shortcuts. In this situation, given that only one pattern is played, the FINGER location would be the most suitable if the equipment does not interfere with steering. Otherwise, the FOREARM location would be more suitable.

7.3 3D Selection in Mixed Reality with microgestures

Interaction based on microgestures combined with gaze is another situation where vibrotactile feedforward and feedback can be interesting. Chaffangeon Caillet *et al.* have designed a 3D selection technique for mixed reality [13] where users perform a back-and-forth flex microgesture of the index to select and reveal a 3-item menu around the object they are gazing at. Performing a localized tap microgesture on different phalanxes of the index then activates a command of the menus.

We adapt the technique by considering taps on different fingers rather than taps on different phalanxes as shown in Figure 8. The technique could be extended by 1) playing a *Discrete dynamic* tacton when users gaze at a target to indicate that a back-and-forth flex microgesture would activate a command, 2) then playing a Short static tacton on three fingers to inform users that a tap on one finger would activate a command. The users can discover how to activate commands without having to gaze somewhere else other than at the target. In this situation, where three different axes need to be distinguished, tactons should ideally be played on the FINGER location, but can also be played on the FOREARM location if the haptic device is not compatible with the microgesture sensing glove [13].

8 CONCLUSION

In this paper, we investigated Tactons and haptic device locations for representing microgestures. Our main goal with this study was to compare 3 device locations and whether various haptic patterns could be recognized and localized on 4 axes. The results show that the users better identify the tactile cues, especially the axes, when the stimulation is on their FINGERS. The HAND and FOREARM locations remain suitable alternatives though. Static patterns showed better accuracy than dynamic ones. The *Continuous dynamic* is the most difficult pattern to identify. Although we have found exploitable results regarding the recognition of both patterns and axes, and have formulated recommendations, we have not yet evaluated these Tactons in use case scenarios. Our next step is therefore to integrate vibrotactile feedback and feedforward in microgesture-based interactions as presented in the scenarios above. To do this, we need to implement the haptic device alongside a microgesture sensing device. This work also paves the way for many other future research possibilities, such as exploring new patterns and new device locations.

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