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Investigating the Haptic Perception of Directional Information Within a Handle

Inès Lacôte, Claudio Pacchierotti, Marie Babel, David Gueorguiev, and Maud Marchal

Abstract—This paper studies the perception of 2-dimensional directional cues presented on a hand-held tangible interface that resembles a cylindrical handle. The tangible interface is designed to be comfortably held with one hand and houses five custom electromagnetic actuators composed of coils as stators and magnets as movers. We carried out a human subjects experiment enrolling 24 participants, analysing the recognition rate of directional cues using the actuators either to vibrate or tap in sequence across the user’s palm. Results show an impact of the positioning/holding of the handle, the mode of stimulation, and the directional indication sent via the handle. There was also a correlation between the score and the confidence of the participants, showing that participants are more confident when recognising vibration patterns. Overall, results supported the potential of the haptic handle to provide accurate guidance, with recognition rates higher than 70% in all conditions and higher than 75% in the precane and power wheelchair configurations.

Index Terms—Keywords: Apparent Haptic Motion, Tactile devices, Assistive Haptics.

I. INTRODUCTION

Providing navigation information through the haptic channel is considered promising as well as beneficial in many applications, as it conveys rich information in a private and distributed manner. It has been successfully employed in navigation [1], guidance in industrial teleoperation [2], locomotion [3], [4], [5], and for the support of people with sensory disabilities. Indeed, as autonomy is one of the most important elements for people with sensory impairments [6], significant effort has been placed to develop tools to assist them in their displacements. Some of these technologies aim at integrating or enhancing existing mobility assistance devices, such as white canes [7], power wheelchairs [8], and walkers [9]. They can help the user follow a predefined path [10]–[12], or notify the presence of possibly dangerous obstacles [8], [9], [13], [14]. For example, Marchal-Crespo et al. [10] developed a robotic wheelchair trainer that guides users along a line drawn on the floor, with kinesthetic cues provided by a force-feedback joystick. Results show that the movements of the joystick, coupled with the haptic feedback, improved the steering ability of children without motor impairment as well as of one child with a severe motor impairment. Kucukyilmaz and Demiris [12] presented machine learning shared control policies from demonstrations offered by a human assistant. They trained a Gaussian process regression

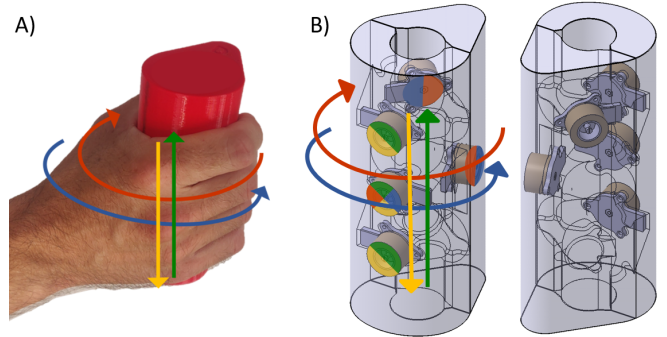


Fig. 1. Haptic handle used to investigate human capabilities of discerning directional information. We considered four directions to recognise: the first two (green and yellow arrows), run vertically along the axial direction of the handle, providing haptic cues across the hand metacarpals; the second two, (blue and red arrows), run around the lateral surface of the handle, providing haptic cues between the thumb and the middle fingers and across the palm. A) A user comfortably holding the handle in a power grasp. The handle is 3D printed using a soft plastic material. B) CAD model of the handle (two views), housing five custom electromagnetic actuators.

model to continuously regulate the level of assistance between the user and the robot, given the user’s previous and current actions and the state of the environment. Results showed that the jerkiness of the user’s joystick movements significantly dropped. More recently, Grzeskowiak et al. [9] proposed a vibrotactile navigation system to augment any walker without requiring modifications of the structure or advanced technical knowledge. Vibrotactile feedback is provided through the handles to indicate the proximity of obstacles on the user’s way.

On the other hand, other works propose independent apparatus for mobility assistance, such as the Animotus [15] and S-Ban [16] systems. The Animotus device resembles a cube with a moving upper half which rotates and extends relative to the bottom half, which is grasped by the user. This change in shape is felt by the user’s fingers and can be employed to represent heading and proximity to navigational targets. Similarly, the S-Ban is a hand-held haptic interface employing a parallel kinematic structure to deliver 2-degrees-of-freedom spatial information, which can be used alone or integrated with other navigation aids. The ability to pivot, extend, and retract its body can provide rich spatial and navigational cues.

The common objective of these navigation systems is to comfortably provide rich navigation information, enabling an increasingly larger set of people with sensory disabilities to attain independence. For these reasons, haptic interfaces for navigation come in different forms, e.g., wearable [5], [8], hand-held or graspable [10], [15], [16], and are able to provide

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a wide range of haptic sensations, such as vibrotactile [8], [9], skin stretch [5], or shape changing [15], [16].

In addition to the form factor, grounding, and actuation capabilities, it is essential to study the best rendering techniques to convey the richest navigation information with the available hardware. In this respect, haptic illusions are considered a promising approach to provide complex sensations through simple actuation paradigms. Often compared to analogue illusions of visual and auditory senses [17], haptic illusions provide indeed a wide range of possibilities to convey new sensations and make haptic interfaces more informative. For example, the apparent haptic motion (AHM) illusion is one of the main tactile illusions used in this context. It has been studied since 1917 by Burt [18] and defined by Lederman and Jones [19] as discrete mechanical or electrotactile stimuli presented sequentially on the skin conveying a sensation of continuous motion. Indeed, the AHM is a powerful tool for conveying directional indications, proven effective on the forearm and the back [20], between two hands holding a tangible object [21], and across the palm [22]. Most often, this illusion is elicited through vibrotactile cues [20], [21], e.g., providing discrete vibrations on a body part elicits the illusory sensation that the vibration moves continuously along the body. However, recently also “tapping” cues were found able to elicit such haptic illusion [22]–[24].

Taking inspiration from these results, this paper studies the human’s ability to discriminate the direction of a haptic stimulation within an object of almost cylindrical shape that a user could hold in his or her hand. We aim at investigating whether users could distinguish directional information in four different directions, as illustrated in Fig. 1.A. For this purpose, we designed a handle housing five custom electromagnetic actuators composed of coils as stators and magnets in their repulsive position as movers, as shown in Fig. 2. Three actuators at a time are activated to convey directional stimuli (along the axial direction of the handle or around the lateral surface of the handle). We considered two types of haptic stimuli, vibrations and tapping, as well as three ways to hold the handle with respect to the body, normal to the sagittal body plane, coronal plane, and transverse plane. As shown in Fig. 4, these three configurations of the handle with respect to the body resemble the way a user holds onto three of the most common mobility aids, i.e., a precane, a walker, and a power wheelchair. Studying how to provide directional information in these configurations will ease the practical translation of these findings for mobility assistance applications.

The outline of the paper is the following. Section II details the experimental device designed for our study. Section III describes the user study while Section IV summarises the results. Finally, Section V discusses the conclusions of our study and presents the perspectives and future works.

II. EXPERIMENTAL DEVICE

We designed a custom handle composed of 3D printed soft material (Filaflex 82A, 0.4-mm thickness). Its shape has been designed to snugly fit the hand and thus it is not a perfect cylinder. The handle houses five custom actuators, distributed

across the structure in dedicated alcove, so as to stimulate the hand in crossing directions (see Fig. 1B. and Sec. III-B).

The custom actuators are composed of coils as the stators and magnets fixed in their repulsive position as the movers (see Fig. 2). Their design is inspired by Duvernoy’s motors for the Hapticomm device [24] and used in previous studies about AHM illusions [22], [23]. This design enables their use *both* as vibratory stimulators and sustained non-vibrating pressure points, e.g., to produce “tap” sensations. Compared to [22], the actuators were improved here by adding a brass guide in the centre of the cavity where the ring magnets rest. Two brass washer with a smaller inner diameter than the magnets’ hole prevent the magnets from falling out of the coil, enabling the use of these actuators in non-vertical positions (cf. Figure 2).

Finally, the actuators use amplifiers with a gain $G_a = 10$, which are connected to a differential -9/+9 V power supply and a National Instrument card for tension control. The output of the amplifiers is a tension varying between 0 V and 6.5 V.

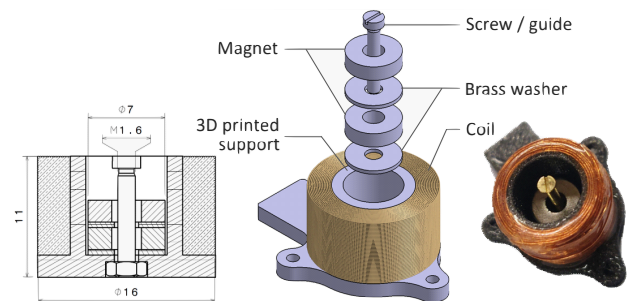


Fig. 2. Custom electromagnetic actuators used in the handle. They are made with 3D printed support, 0.22 mm wire, two magnets, two brass washers, and a brass screw. The brass guide and the two brass washer running through the centre of the cavity prevent the magnets from falling out of the coil, enabling the use of these actuators in non-vertical positions.

III. USER STUDY

Our experimental evaluation aims at investigating the human ability to recognise the stimulation direction induced through the asynchronous activation of the actuators in the handle. The study has been approved by Inria’s ethics committee (COERLE, approval number: 2021-39).

A. Experimental methods

As already anticipated in Sec. I, we considered two types of haptic sensations (vibrations, taps), three positioning/configuration of the handle with respect to the user’s body (resembling how a user holds a precane, walker, wheelchair joystick), and 2×2 directions (two along the axial direction of the handle, two around the lateral surface of the handle).

Type of haptic sensations. We considered two different ways of providing haptic cues. Vibrations are generated by the actuators at 120 Hz, sending the input tension as a 120 Hz sine signal within a ramp envelop (see [23] for details). On the other hand, taps are generated by the actuators as non-vibrating pressure point induced by maintaining a 6.5 V command for 220 ms, which results in a light but perceivable tap (see [22]).

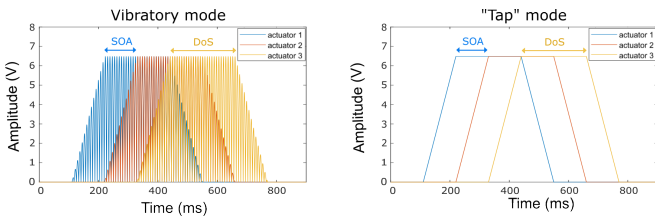


Fig. 3. Example of vibratory and "tap" signals sent to three actuators for a given direction presenting both actuation modes. The Stimulus Onset Asynchrony is $SOA = 110ms$ and the Duration of Stimulus is $DoS = 220ms$.

Positioning of the handle. We considered three different ways of positioning the handle, normal to the sagittal body plane, coronal plane, and transverse plane, which resemble the way a user holds onto a precane, a walker, and a power wheelchair, respectively (see Fig. 4).

Navigation direction. We considered four directions of motion. The first two directions, *green* and *yellow* arrows in Fig. 1, go along the axial direction of the handle, corresponding to a stimulation across the metacarpals; the two other directions, *blue* and *red* arrows, run around the lateral surface of the handle, for stimulations between the thumb and the middle fingers passing through the centre of the palm.

B. Experimental task and design

Participants were asked to hold the handle in a power grasp and determine the direction of the stimulation, answering with a numerical pad in front of them. They were also provided with a picture similar to Fig. 1, adapted for the handle positioning currently under examination, so as to better understand which keystroke represented which direction. A participant carrying out the experiment is shown in Fig. 5. After they selected a direction, participants were also asked to rate their confidence in the response using a 9-point Likert scale.

The experiment is composed of three parts, each corresponding to a position of the handle (precane, walker, wheelchair). For each part/position, the participants carried out eight blocks of 16 stimulations each: four blocks with vibratory signals and four blocks with "tap" signals. Each

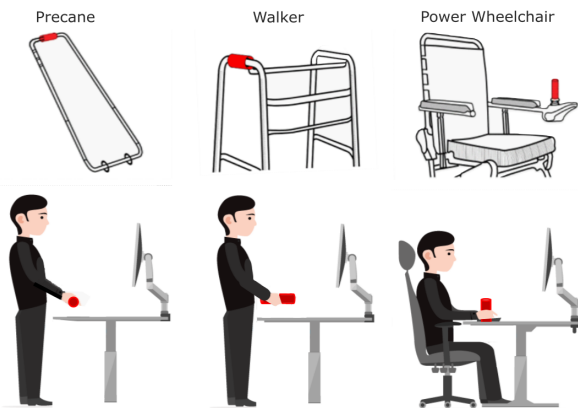


Fig. 4. Positions of the participant holding the handle (in red) during the experiment. These three configurations of the handle with respect to the participant's body match the way users commonly hold onto a precane (left), walker (centre), and power wheelchair (right).

block is composed of four repetitions of the four directions presented in a randomised order. After every part, the participants take a break and start the new set of blocks with a new positioning of the handle. This experimental protocol leads to 3 (handle position) \times 2 (sensation type) \times 4 (blocks) \times 4 (directions) \times 4 (repetitions) = 384 recognition trials.

C. Participants and experimental procedure

Participants started the experimental session by reading and signing the consent form. They answered demographic questions and a form to identify their dominant hand as well as possible haptic sensory impairments. Finally, they started the recognition experiment as detailed in Sec. III-B.

We enrolled 24 participants between 21 and 54 years old, nine being women, three left-handed, and two ambidextrous. Their dominant hand was determined by to a 10 questions questionnaire about their daily habits. The two ambidextrous participants had more "right hand" answers than "left hand" or "no preference" answers. For this reason, we decided to make them use their right hand for the experiment. None of the participants had lesion or tactile perception loss on their dominant hand. The experiment lasted between one hour and one hour and a half. The participants were naive about the objectives and hypotheses of the study. During the experiment, they wore noise-cancelling headphones and faced two screens: one visualising their answers and one showing the four directions to choose on a picture of a user holding the handle (similar to Fig. 1). All participants completed the task. The presentation order of the three handle positions was counterbalanced between participants; half of them started with the vibratory stimulation and half with the "tap" stimulation.

The data collected from the participants were the numbers on the keypad corresponding to the direction they perceived (2-*red*, 4-*green*, 6-*yellow* or 8-*blue*) and their confidence from 1 (no confidence at all) to 9 (total certainty). At the end of the experiment, participants also gave open comments and feedback about their sensations and the experiment in general.

IV. RESULTS

This Section presents the recognition performance of the directional cues presented by the handle.

Results overview: First, to have a global overview of the data, we generated a confusion matrix of the participants' answers, shown in Fig. 6. As we can see, the majority of answers are present in the diagonal from the top left to the bottom right, corresponding to the correct answers. However, we can also clearly see that the other diagonal contains several answers. This means that most of the errors done by the participants come from detecting the correct sequence of motors but with the wrong direction, i.e. mixing *red* with *blue* and vice-versa, as well as *green* with *yellow* and vice-versa (see Fig. 1). Other errors corresponding to the other cases of the matrix are less numerous.

Generalised Linear Mixed Model: We studied the participant responses using a generalised linear mixed model (GLMM). Since the dependent variable is a binary categorical

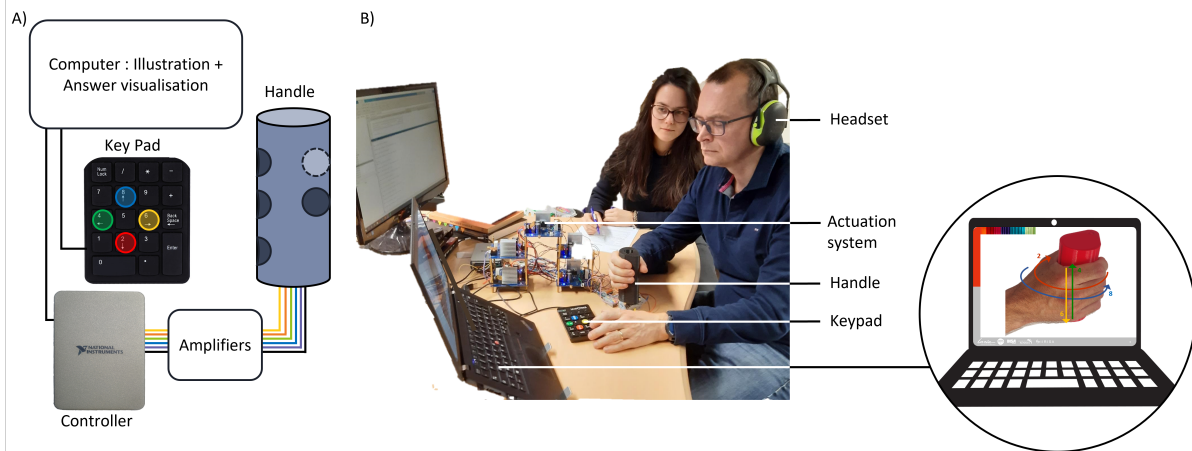


Fig. 5. Experimental setup for the user study. The handle houses 5 electromagnetic actuators, attached to a set of amplifiers controlled by a National Instrument card NI 9264. Participants are asked to hold the handle according to the considered positioning (“wheelchair” in this Figure, see also Fig. 4) and recognise the provided direction. The answer was registered using a numerical pad.

		Participant Answer			
		Red	Green	Yellow	Blue
Sent Direction	Red	1665	114	104	421
	Green	51	1828	349	76
	Yellow	68	524	1639	73
	Blue	440	83	124	1657

Fig. 6. Confusion matrix across all trials from the study of the true directions sent to the participants and their answers for the two modes: vibrations or pressure points (“taps”). Directions *green* and *yellow* run vertically along the axial direction of the handle to stimulate the hand metacarpals; directions *blue* and *red*, run around the lateral surface of the handle stimulating the thumb and the middle fingers and across the palm (see Fig. 1).

variable, a binary logistic model was chosen. Independent variables were the direction of the apparent motion (*green*, *yellow*, *blue*, *red*), the position of the handle (precane, walker, wheelchair), and the stimulation mode (tap or vibration). Participants were considered as a random effect in the model. We performed an analysis of deviance, showing statistically significant effect of the mode ($df = 1$, Wald Chi-Square = 137.56, $p < 0.001$), direction ($df = 3$, Wald Chi-Square = 52.20, $p < 0.001$), and position ($df = 2$, Wald Chi-Square = 12.24, $p = 0.002$).

Post-hoc analysis: The parameters that we considered for the handle’s test showed an impact on each other. We performed a Wilcoxon repeated-measures post-hoc analysis showing a significant effect of the handle position between the precane and the walker ($W = -3010$, $p = 0.0146$) on the performance in identifying the correct directions, highlighting better scores in the precane position as shown in Fig. 7.A). Secondly, a similar post-hoc analysis showed a significant effect of the mode of stimulation ($W = -17732$, $p < 0.001$), highlighting the fact that vibratory cues tend to be easier to

classify (cf. Fig. 7.B)). Finally, the analysis showed that the score for direction *green* was significantly different from the other directions: *green* VS. *red* ($W = -2896$, $p = 0.003$), *green* VS. *yellow* ($W = -3213$, $p < 0.001$), *green* VS. *blue* ($W = -3043$, $p < 0.001$), showing the fact that the direction *green*, through the metacarpals from the little finger to the index is the direction best recognised during the experiment (cf. Fig. 7.C)).

Confidence rate: Finally, we looked more into the correlation between the score and the confidence rate of the participants for each answer, presented in Fig. 8.A for the vibrations and 8.B for the “taps”. A linear regression analysis showed a correlation with a factor $r = 0.44$, where we also found through a Wilcoxon analysis, that the mode had a significant effect on the confidence rate ($W = -30790$, $p < 0.0001$) as shown in Fig. 8.C). Our analysis showed a higher confidence when receiving vibratory cues (cf. Fig. 8.C)).

Learning effect: We also wanted to see if there could be a learning effect during the experiment and thus studied the evolution of score. Considering the entire experiment, we found no significant evolution of the score throughout the experiment in this respect. However, when looking at the evolution along the four consecutive blocks of each mode, it appears that participants scored better towards the end of “tap” stimulations, showing a possible learning phase (Fig. 8.D, $p = 0.0271$). Such effect was not found with the vibratory signals ($p = 0.1544$).

V. DISCUSSION

The human subject study enrolled 24 participants testing the recognition performance on three different positions of the handle with both vibratory signals and “taps” cues. The objective of the experiment was to study the impact of handle position and the different modes of stimulation on the tactile perception of directional information on a handle.

Results showed that the position of the precane is better than the walker to receive the directional information through our handle, i.e., it leads to better recognition rates. A possible explanation is that, despite the improvements in the design of the motors with respect to [22] (see Sec. II), work is

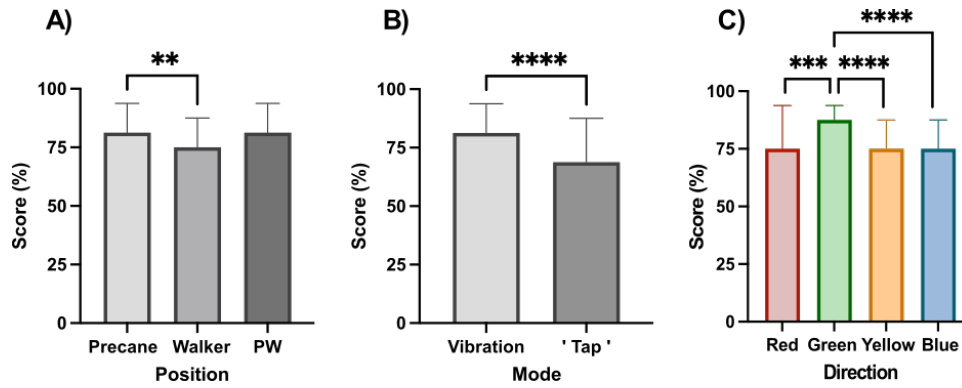


Fig. 7. Score results: barplots using the median value and the interquartile range for the error bar. A) Score for the different positions of the handle (PW = power wheelchair). B) Score for the two modes of stimulation. C) Score for the different directions conveyed via the handle. All scores are given in % of correct answers. Statistically significant differences are indicated with ** when $p < 0.01$, with *** when $p < 0.001$ and with **** with $p < 0.0001$.

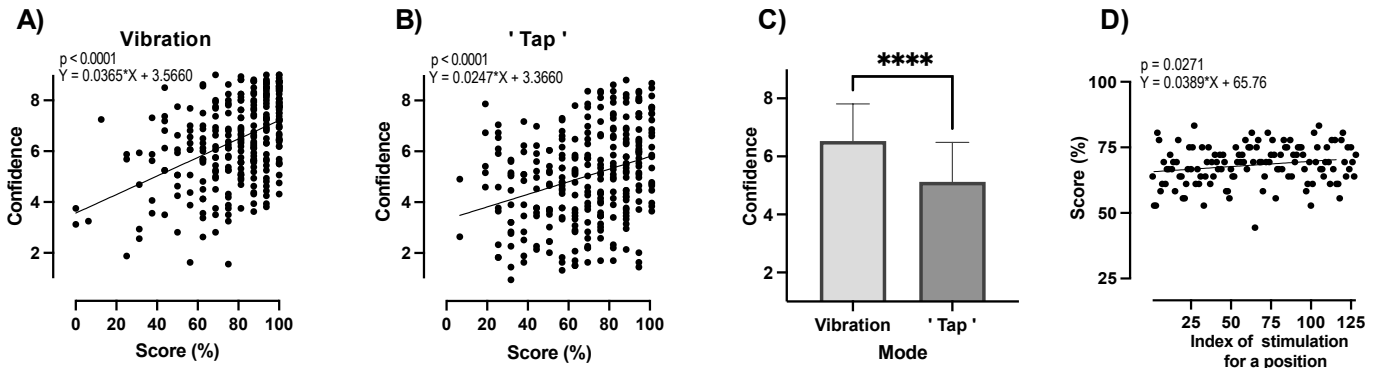


Fig. 8. A) Correlation between score and confidence for vibratory cues. B) Correlation between score and confidence for “tap” signals. C) Confidence of participants for the two modes of stimulation. The results are given with barplots using the median value and the interquartile range for the error bar. D) Evolution of the scores along the four blocks of stimulations for “taps” signals.

still needed to enable a flawless omnidirectional use of those actuators. Indeed, when turning the handle to the walker or power wheelchair positions, the majority of the actuators are facing the side or down, which might affect their performance. Such additional improvements could also respond to the difference of efficiency of the motors between the vibratory and the “tap” modes, specifically maintaining higher constant force when using “tap” stimulations. Indeed, even though the 3D printed membrane is soft, its stiffness still reduced the force exerted by the magnets on the skin, especially in upside-down positions and when the “tap” signals was played. Despite these limitations, in all the considered conditions, the large majority of the participants were able to recognise the rendered directions (all $> 70\%$). This performance overcame our expectations given the difficulty of the proposed task and pave the way for the integration of the handle into the considered mobility aids.

From the confusion matrix of Fig. 6, we can also appreciate that most incorrect answers are due to an error in identifying the correct direction of motion, meaning that participants could anyway still differentiate between the two dimensions. Our statistical analysis also highlighted that the *green* direction, along the handle from the fifth metacarpal to the first one (on the palm, from little finger to index), was the easiest direction to identify and where participants scored significantly better. This result might be due to the fact that humans are more used

to receive vibration patterns that move in this direction, e.g., tapping with a cane or umbrella on the ground.

We also found an interesting correlation between the score and the reported confidence, with vibrations leading to both better scores and confidence rates. Finally, the study of potential learning effects showed that there were no strong evolution of the score throughout the whole experiment. However, if we consider the “tap” stimulation alone, a significant increase of the score was highlighted along the four consecutive blocks of stimulation with this mode. These two results together, i.e., participants recognising vibration patterns with more confidence and a learning effect on the “tap” mode, might mean that participants are less used to be guided by “taps.” This insight opens an interesting question regarding the study of less common/used haptic patterns, which might – at a first glance – seem less efficient than other more common ones such as localised vibratory points for 3D directional information [25] or left/right armband [26], but only because of the lack of training.

At the end of the experiment, we also gathered free comments from the participants, which were rather different from one person to another. Some of the participants preferred “taps” over vibrations when others preferred vibrations, but very few were able to explain why. People with larger hands tended to be more tense and have a less relaxed position on the handle. The size and shape of the hand with respect to

the handle is another interesting aspect that we would like to take into account. Indeed, the personalisation of the haptic rendering is an open and interesting topic in the field [27], which is even more relevant when addressing the very different needs of people with sensory disabilities.

VI. CONCLUSIONS AND FUTURE WORK

This paper investigated the ability to identify directions conveyed on the volar side of the hand via the asynchronous activation of discrete contact points on the skin. A 3D printed handle, made of soft material, housed a set of custom designed electromagnetic actuators and enabled a comfortable grasp by the user. We carried out a human subjects study to evaluate the recognition rates of four directions rendered on the handle by the motors, conveying vibratory signals or “taps” cues, when the handle was held in three different positions. These three positions of the handle with respect to the body resemble the way a user holds onto three of the most common mobility aids, i.e., a precane, a walker, and a power wheelchair, enabling a faster practical translation of these results for mobility assistance applications.

Results supported the feasibility of the proposed approach, with recognition rates higher than 70% in all conditions and higher than 75% in the precane and power wheelchair configurations. With respect to the feedback, providing vibrations outperformed “tap” sensations, which might be partially due to humans being generally more used to follow and interact with vibrations stimuli.

Future research will tackle different aspects of this work, starting from the integration and evaluation of this technology in mobility aids. Other relevant aspects to address are the personalisation of the haptic rendering and of the handle design, the improvement of the custom actuators for omnidirectional use, and the use of innovative materials to better isolate the stimulation so as to enable finer perception.

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