”Tap Stimulation”: An Alternative To Vibrations To Convey The Apparent Haptic Motion Illusion

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***Abstract*— Vibrotactile sensations can be used to elicit apparent haptic motion illusions, which consist in using discrete vibration patterns to convey an illusory continuous moving sensation across the skin. However, experiencing prolonged vibrations is also known to increase the cognitive load. This study investigates whether continuous mechanical stimulations, or taps, that are activated in sequence, can also create a convincing illusion of haptic motion across the skin. Moreover, we also test whether an increased curvature of the contact surface impacts the quality of the felt illusion. We conducted a comparative psychophysical experiment enrolling 18 participants showing that the proposed "tap" stimulation was as efficient as a 120 Hz vibrotactile stimulation in conveying the haptic motion illusion. Moreover, results showed that the curvature of the contact surface had little effect on the quality of the sensation. Thus, using continuous mechanical stimulations that do not vibrate can be a good alternative to vibrations for rendering haptic sensations in hand-held devices in a lot of applications including navigation guidance.**

I. INTRODUCTION

Tactile stimulations often rely on the use of haptic illusions, as they constitute a major mean of enriching devices and their transmitted messages [1], [2] in various applications. One of these illusions is the Apparent Haptic Motion (AHM), which has been a research interest since 1917 [3], [4]. This illusion consists in actuating asynchronously discrete stimulation points on the skin. With proper parameters of time delay and duration, it is possible to convey a sensation of continuous motion along a line delimited by the activation of separated contact points stimulated on the skin [5]. As a 1D or 2D motion [6], AHM is an interesting tool to indicate directional cues and provide a sensation of movement in applications such as navigation assistance. Studies demonstrated that the AHM illusion can be very well perceived on different body parts such as the arm [7], the hand, and the back [8], where it was found to convey clear directional cues, when stimulated with vibrotactile actuators. Indeed, in navigation tasks, passive touch is used so that users do not have to search for the information, but instead can keep their attention on the mobility task while passively getting the complementary indications [9]. Tactile stimulations have been found to be a great tool to assist navigation, as they are easy to understand and implement [10], [11], [12]. The main goal of technologies that rely on vibrotactile feedback is thus to improve the amount of information delivered by the device while staying intuitive, clear, and comfortable through the use of various patterns and stimulation methods for various applications, such as virtual reality or navigation indications. Researchers are precisely investigating these thematics with various technologies such as the small device Buru-Navi3 for navigation guidance [13] or embedded vibrations onto mobility assistance devices like powered wheelchairs [14] and white canes [15].

However, when transmitting complex vibratory messages or combining multiple vibrotactile signals, there is a risk of altering the perception or creating tactile noise referred to as tactile *clutter* [16], especially during prolonged use as in navigation tasks. Thus, an interesting research topic is to find whether another way of stimulation could be a viable, informative, and comfortable alternative to vibration when it comes to conveying apparent haptic motion.

Based on this assessment, this study aims to compare the state of the art vibrotactile apparent motion with a continuous mechanical stimulation, that will be referred to as "tap" stimulation, which already has been investigated for other applications with pin arrays [17], [18].

The goal of this paper is to test the robustness of the illusion on multiple curvatures, e.g., for usage on handle-like devices, as the AHM literature mainly focuses on flat surfaces. Gallo et al. [15] developed a smart cane integrating technologies that rely on the AHM mechanism, however, they did not study the impact of curvature. Besides, this study aims to compare stimulation modes to understand if vibrations are a main condition for obtaining AHM illusions or if a "tap" stimulation, as that used in haptic communication of people who are deaf-blind [19], could be one of the viable alternatives we are looking for.

To that aim, we propose a study with two main objectives conducted on 18 participants, with the setup presented in Fig. 1. First, we compare the vibratory mode and the "tap" stimulation to convey the apparent haptic motion on the hand. Secondly, we study the impact of bending the contact surface on the perception of the illusion, by using a flexible hand-rest that we position on five different curvatures.

The paper is organized as follows. Section II presents the materials and methods of the user study, Sec. III the results and statistical analysis across the considered conditions, and finally Sec. IV discusses the results and proposes future directions and perspectives.

II. USER STUDY

This study aims to compare the effectiveness of vibratory and continuous mechanical stimulations, referred to as "tap" stimulations, for eliciting an apparent haptic motion illusion. The study has been approved by Inria's ethics committee

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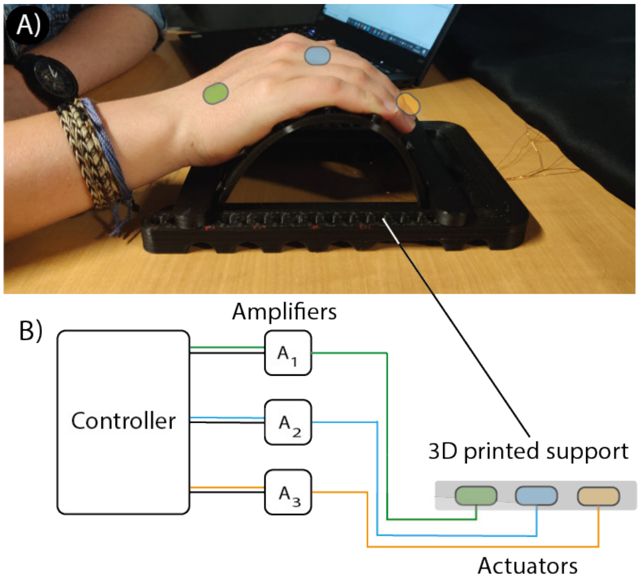


Fig. 1: A) The experimental setup is composed of 3 electromagnetic actuators placed on a flexible hand-rest, adaptable to various curvatures. The participants answer to questions regarding the illusory effect on a GUI interface located in front of them. The colored dots show the contact points of the actuators on the hand. B) The signals are generated via a controller, then amplified before being played by the custom-built actuators.

(COERLE Dornell - Saisine 513). Three different contact points on the palm and the middle finger are stimulated to convey the apparent haptic motion illusion either through subsequent vibrations or "taps". Only one type of motor was used to provide both types of stimulations, to keep the experimental set-up as similar as possible between the stimulation modes.

A. Experimental setup

The experimental setup shown in Fig. 1 is composed of three custom actuators inspired by Duvernoy's [18], with a coil as a stator and two magnets glued together in their repulsive position as a mover to increase the magnetic field. A representation of the actuators is given in Fig. 2. The actuators are mounted onto a flexible 3D printed hand-rest which is set to 5 different curvatures during the experiment, as shown in Fig. 4. The commands for the three actuators are created via Matlab and then provided through a National Instrument USB-6343 series controller, which sends them to three amplifiers enabling to deliver a 6.5V signal to the motors, corresponding to a force of approximately 0.4 N exerted on the palm and the finger. Fig. 3 presents the superposed force data of five activations of an actuator recorded with a Nano17 force sensor (ATI, USA) at a sampling rate of 5000Hz. The two magnets of the electromagnetic actuators go upward and downward in the center of the coil depending on the electrical tension passing through it. This design enables to implement the two stimulation modes for the study: (i) the vibratory mode and (ii) the

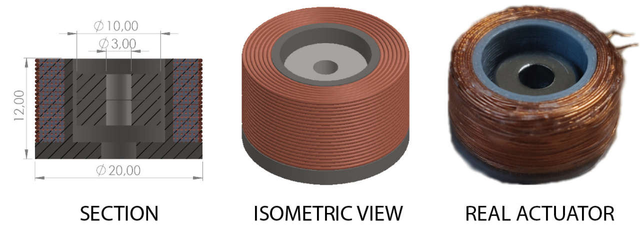


Fig. 2: CAD and picture of the custom electromagnetic actuators. The coil structure (dark grey) is 3D printed, and two magnets (light grey) glued in their repulsive position constitute the mover. The designed is inspired by Duvernoy [18]. Dimensions are in mm.

"tap" mode. The vibratory mode consists of an oscillation of the magnets at a chosen frequency. This is implemented with the tension signal following a sinusoïdal carrier in a ramp envelop, see Fig.5a. The second mode, also called "tap" mode, corresponds to a unique upward displacement of the magnets inside the coils, which is maintained during a time period given by the Duration of Signal (DoS), before going back to their resting position, see Fig.5b. The two modes provide asynchronous stimulations at the same three locations on the hand (see Fig. 1). For both stimulation techniques, overlapping ramp activation of the voice coil actuators are implemented, as illustrated in Fig. 5. The time delay between the actuators, also called Stimuli Onset Asynchony (SOA) and DoS are fixed parameters.

Based on pilot tests and [15], which investigated apparent motion for augmenting a walking cane, we set the SOA and the DOS parameters to $SOA = 110$ ms and $DoS = 220$ ms in both stimulation conditions. A review of various studies on apparent haptic motion with vibrotactile stimulations [20] helped determine the vibrating frequency of the motors along with some pilot tests, so as to ensure that frequency and intensity were pleasant for the user. Finally, the vibration frequency was set to 120Hz. A unique maximum intensity of the signal at 6.5V is used during the entire experiment.

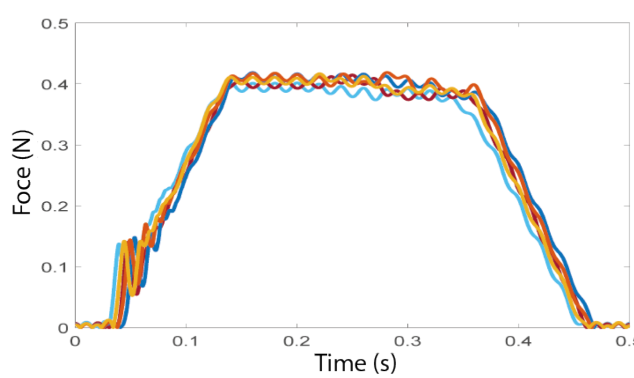


Fig. 3: Characterized force feedback for "tap" stimulations. The curves represent five consecutive trials.

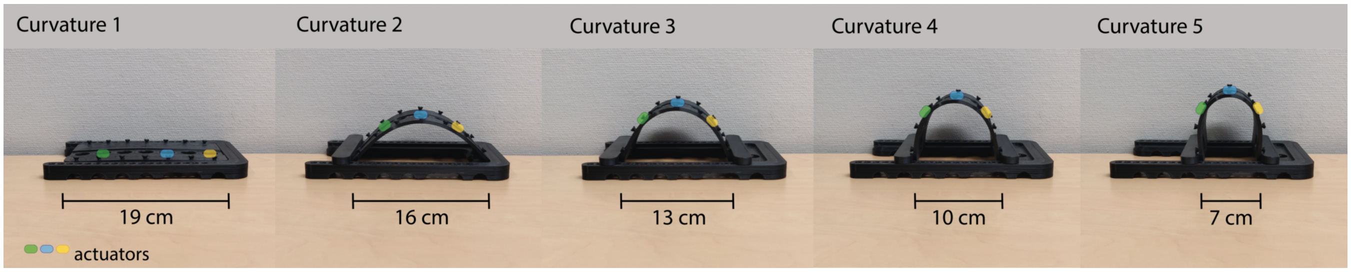
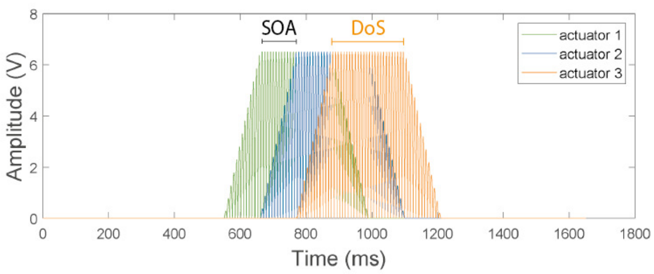
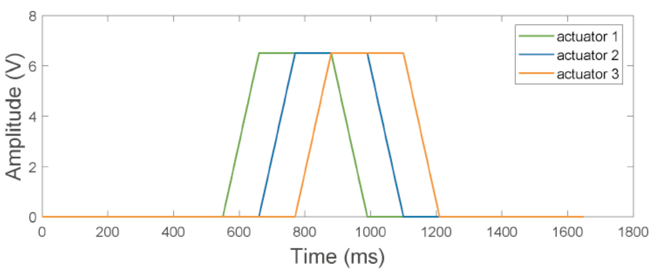


Fig. 4: Flexible 3D printed hand-rest on the 5 tested curvatures, from flat to curved.



(a) Vibratory mode made of sinusoïdal oscillations at 120Hz within ramp envelops.



(b) "Tap" mode made of ramp signals.

Fig. 5: Signals sent to the three actuators for both actuation modes.

B. Experimental design

The experiment is designed so that the stimulations are conveyed along the middle finger to the bottom of the palm and tests several conditions. Besides (i) the two ways of stimulating (vibratory and "tap"), we also consider (ii) five different curvatures of the contact surface (Fig. 4) and (iii) two directions of motion. (ii) The five curvatures are obtained by bending the flexible hand support in which the motors are embedded. The obtained distances between the top and the bottom of the flexible support, as a result of the bending, are respectively 19 (totally flat, Curvature 1 in Fig. 4), 16, 13, 10, and 7 cm (fully curved, Curvature 5 in Fig. 4). The curvatures are chosen to range from the standard flat position to a curvature that resembles the one of a handle or joystick.
(iii) The two directions are either proximal or distal along the hand (green towards orange or orange towards green in Fig. 1). They are described to the participants as "upward" and "downward" directions as well as represented on a drawing. The time delay between the actuator activation (SOA) and the duration of the signals (DoS) being constant, the speed of the illusory motion is a fixed parameter. Finally, the signal maximum intensity is given at 6.5V for all stimulations making the signal amplitude also constant.

Globally, the study is organized to test the changing parameters as following. The curvatures are tested one after the other and their presentation order is pseudo-randomized and counterbalanced across participants to avoid habituation or learning effects. For practicality, the two modes (vibrations or "taps") are tested one after the other in a random order on a specific curvature, before the curvature is modified. A testing block is composed of 6 trials of which the only changing parameter is the direction. A block is thus made of only vibratory or only "tap" trials of which three are identical distal stimulations and three are identical proximal signals. Thus, blocks are differentiated by the type of signal that is provided (vibratory or "tap") and by the curvature of the support (curvature from 1 to 5). The order of the six trials is also pseudo-randomized in each block. Moreover, a trial is made of three repetitions of the AHM pattern stimulation, to be sure the participants are able to perceive well the signal before answering

C. Participants

Eighteen persons participated in the experiment, of which eleven were women, between twenty-one and fifty-seven years old, and one was left-handed. Stimulations were delivered on the dominant hand, determined with a questionnaire before the experiment. None of the participants have had trauma on the tested hand that could affect his/her tactile perception. Participants were naive about the objectives and hypotheses of the experiment and had not seen or tried the setup before participating in the study.

D. Experimental procedure

Participants carried out the experiment in a dark room, with a box placed above the setup, so that they could not see the device before or during the experiment. They also wore noise-cancelling headphones to avoid any auditory information about the received stimuli. They received no indication about the number of embedded motors in the setup nor about the number of activated ones, but they were told that the number would not vary within a block. Indications about the global number of stimulations and repetitions were given before the experiment along with the sum-up of the questions participants would face during the test. A Matlab script manages the transmissions of signals to the National Instrument controller card and stores the characteristics of the trials sent as well as the answers to the questions. The presentation order of the five curvatures is given when launching the script for a user.

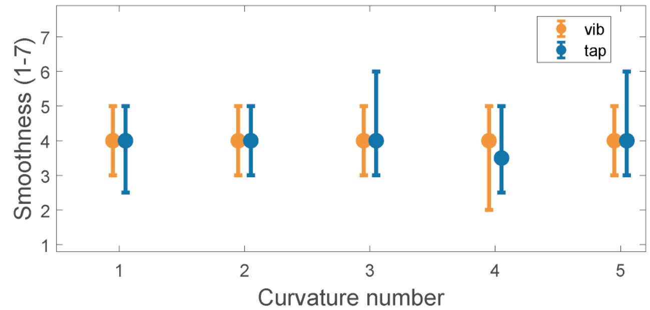
To begin with, the first curvature is set on the flexible hand-rest. The participants keep the hand in a static position upon the support after the investigator had positioned it correctly on the hand-rest. The correct positioning of the hand is checked throughout the experiment. After each trial, the participants answer two questions about what they perceived: (i) What was the direction of the stimulations ? (ii) Rate the smoothness of the apparent motion generated by this particular trial on a seven-points Likert scale, from 1 (discrete) to 7 (continuous). Here the evaluated parameters are the curvature, the mode of actuation and the direction of the motion. After the sixth trials, corresponding to the end of the block, participants are asked to rate three other perceptual dimensions of their tactile experience during the block: (iii) the ease to answer the up/down question from 1 (very difficult) to 7 (very easy), (iv) the pleasantness of the stimulation 1 (very annoying) to 7 (very pleasant), and finally (v) the fatigue perceived on their stimulated hand from 1 (not tiring at all) to 7 (very tiring). For this second part, the evaluated parameters are the curvature and the mode of actuation. The directions being mixed within a block, it is not evaluated for those questions. This process is repeated for the other mode of stimulation and on the 5 curvatures, which are tested in pseudo-random order.

The data is then processed and organized to create the matrix of interest to study the impact of the curvatures, the difference of perception of the two stimulation modes and the effect of the direction of the pattern. The participants were also able to give free comments and feedback about their sensations and the experiment at the end of their participation to the study.

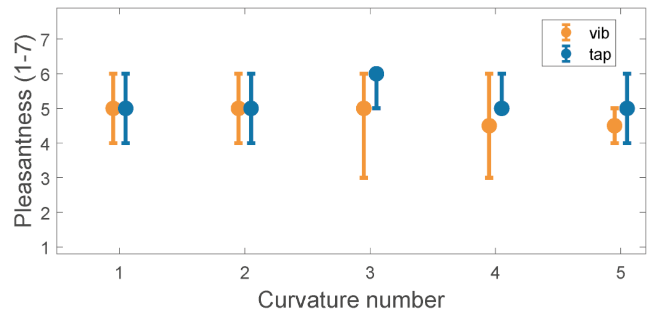
III. RESULTS

The results showed that whatever the curvature and the signal type, the participants could perfectly sense the direction of the apparent motion, as the median, first and third quartile of scores were all at 100% of success. Thus, the quality of the AHM illusion was assessed by the additional questions to which participants had to answer.

For each of these questions, we performed a Generalized Linear Model (GLM) statistical analysis on the independent variables of our study. For the smoothness score, which was answered after each trial, these variables were the curvature, the mode of stimulation and the direction of the movement. The GLM analysis showed no statistical effect of curvature (p=0.450), nor an effect of the stimulation mode (p=0.484). Only the direction of the stimulation showed a weakly significant effect on the perceived smoothness. To investigate further this effect, we performed a post-hoc statistical analysis that confirmed that the perceived smoothness was significantly different (Mann-Whitney ranked test: U = 135349, p = 0.038) between the two directions of stimulation. Its score was 3.85 $\pm$ 1.53 when stimulating distal AHM and 4.05 $\pm$ 1.60 for proximal AHM. Interestingly, both stimulation techniques showed an identical perceived level of smoothness that corresponds to a slightly above average perception of smoothness reported in Fig.6a.



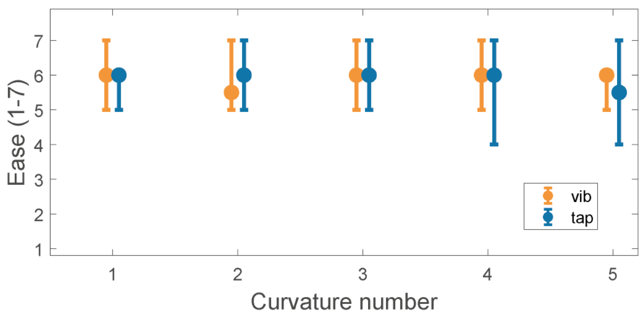
(a) Perceived smoothness.



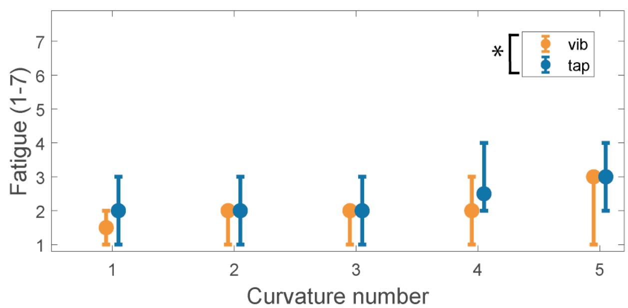
(b) Perceived pleasantness.

Fig. 6: Rates on a 7-point Likert scale for the AHM. The smoothness was rated after each trial of the experiment and each data point is averaged over an experimental block. The middle points correspond to the median value while the error-bars give the 1st and 3rd quartile. Same plot was made for the pleasantness.

A similar GLM analysis was performed on the answers of the other questions about the pleasantness (Fig. 6b), the ease to answer (Fig. 7a) and the induced fatigue (Fig. 7b). Since these questions were answered after experimental blocks that mixed the two directions of stimulation, we considered solely the stimulation mode and the curvature as independent variables. The GLM analysis only showed a significant effect of the amount of curvature on the fatigue (p=0.009). In the subsequent post-hoc analysis we only found a significant effect of the curvature (Friedman test $n = 18$, $Q(4) = 11.47$, $p = 0.049$) for fatigue results when using “tap” signals. However, the influence of curvature on fatigue was not found significant when stimulating with vibrations (Friedman test $n = 18$, $Q(4) = 5.515$, $p = 0.24$). As a consequence, the “tap” mode was found to be slightly more tiring: Wilcoxon matched-pairs signed rank n = 90, W = -364, p = 0.0018.



(a) Perceived ease to find the direction of the AHM.



(b) Perceived fatigue on the hand.

Fig. 7: Rates on a 7-point Likert. The middle points correspond to the median value while the error-bars give the 1st and 3rd quartile.

IV. DISCUSSION

A. Impact of the hand-rest curvature

An important objective of this paper was to determine whether the curvature of a hand-rest would have significant impact on the perception of the apparent haptic motion on the hand. To better understand the perceptual strength of the apparent motion, we conducted a study to test the illusion with parameters validated by other studies like Gallo et al.'s [15] on a hand-rest taking 5 different curvatures. It was decided to use a flat surface as one of the 5 hand-rest positions, to have a reference model that could easily be transposed to the existing literature. Secondly, we tested bending that went until the highest curve of the support, still enabling the magnets to remain in the coil despite of gravity. The palm and the middle finger were chosen to be the stimulated zone because some studies already exist about the AHM on the hand. Moreover, this area being the largest on the hand, it enabled separating the stimulation points to their maximum distance for two reasons: testing the maximum robustness of the illusion with few amount of material and to be free of electromagnetic interference considerations. The study, conducted on 18 participants, tested, between other elements, the clearness and comprehensibility of the direction conveyed on the 5 curvatures. It showed no significant impact of the bending on the perception of the directional cues, neither did it have effect on the perception difficulty, pleasantness of the stimulation or perceived smoothness. An effect was statistically found on the fatigue perceived on the highest curvatures. This might be due to the increasing circularity of the AHM but it is also possible that the sensation was mainly unpleasant because of the uncomfortable wrist position that participants felt was causing fatigue. Overall, the apparent motion illusion was found to generate surprising stable perception across every bending of the contact surface.

B. Comparison of the two modes of stimulation

Besides being widely tested on flat surfaces, experiments on the apparent haptic motion were mainly conducted with vibrations and proved its efficiency. However, vibrations are also known to engender various difficulties when used for an extended period of time, such as sensation of fatigue or tactile noise which can sometimes be confusing. An interesting solution to this issue would be to find an alternative method to the vibration. In this study, we propose a mode of stimulation that does not constantly vibrate and thus compare two modes of activation that are the vibratory stimulations and a continuous mechanical stimuli causing a "tap" stimulation. For every mentioned curvature, participants scored equally on the direction questions. Besides, the "tap" stimulations were found to be as smooth, easy to understand, pleasant as the vibratory mode. Only the fatigue experienced by participants was slightly higher with the "tap" mode, especially for the most curved contact surfaces. However, since the task was easy and participants' fatigue was very low in both modes, this difference might be due to the transient nature of the changes in the "tap" mode.
For their free comments, several participants reported that the "taps" were perceived as more delicate stimulations and that their amplitude was felt lower than the vibrations'. As a consequence, some of the participants suggested the vibrations appeared more as alert signals.

C. Impact and applications

The apparent haptic motion and the conclusions of this study represent a crucial point of interest for many applications like navigation indications [13], [15] ; but it can also answer an increasing and essential need that is the assistance for people who have sensory impairments. Indeed, the prevalence of sensory impairments in the world population is predicted to significantly increase in the following decades [21], [22], urging for solutions to augment the independence capabilities of people affected by sensory deficiencies. Moreover, the loss of autonomy and the lessening of communication capabilities are proven to lead to a multitude of other issues, such as depression and psychological disorders [23]. Communication and navigation tasks represent the two essential points of interest for people with visual or auditory impairments, because their lessening is the leading cause of isolation and autonomy loss. Research is actively looking for methods and devices to convey indications for navigation and communication through various stimulation modalities such as audio and touch. For example, some systems implement audio descriptions or alerts, like the WeWalk smart cane [24] ; but it appears that haptic devices are a key solution to inform people without interfering with other engaged sense during the navigation. Haptic devices are investigated such as the smart cane from Gallo et al. [15] or smaller devices like the Buru-Navi3 from Amemiya et al. [13] and the Animotus from Spiers et al. [25] for navigation guidance or the HaptiComm device from Duvernoy et al. [19] for communication. This study provides a new insight about perception for the optimization or development of such technologies in the context of navigation assistance but also haptic interfaces for people with sensory impairments.

V. CONCLUSION

The apparent haptic motion (AHM) has been studied for a long time and its robustness has been widely showed on many surfaces and flat objects. Indeed, when using specific values of the signal's temporal parameters, i.e. the time delay between the activation of actuators, the duration of the signals, and the vibratory frequency, the illusion provides a movement sensation along the line drawn by the actuator positions, even though only discrete points are actually stimulated. In this study, we wanted to explore the perceptual limits of the AHM illusion. To that end, we investigated the effect of the hand-rest curvature on the perception of the apparent haptic motion on the hand. Besides this, we also investigated whether the vibration is a mandatory component to convey this illusion. Thus, a continuous mechanical stimulation induced by sustained pressure of the actuator on the finger was implemented in the study. Participants' answers suggest that the illusion has a high robustness over varying curvatures since all participants were able to perfectly discriminate the direction of the movement on their hand in all conditions of the experiment and the additional questions did not show strong differences. Moreover, participants found the two stimulation modes equally smooth, pleasant and with a similar ease for discriminating the motion direction.

To summarize, the AHM illusion holds over a large range of curvatures and the "tap" stimulation is found to be possible alternative to vibrations. Future research will focus on developing improved actuators to deliver the "tap" stimulation and on investigating whether AHM speed differences are similarly discriminated in the two modes.

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