"I see where this is going": a psychophysical study of directional mid-air haptics and apparent tactile motion

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***Abstract*—Mid-air haptic technology can render a plethora of tactile sensations including points, lines, shapes, and textures. To do so, one requires increasingly complex haptic displays. Meanwhile, tactile illusions have had widespread success in the development of contact and wearable haptic displays. In this paper, we exploit the apparent tactile motion illusion to display mid-air haptic directional lines; a prerequisite for the rendering of shapes and icons. We present two pilot studies and a psychophysical study that contrasts a dynamic tactile pointer (DTP) to an apparent tactile pointer (ATP) in terms of direction recognition. To that end, we identify optimal duration and direction parameters for both DTP and ATP mid-air haptic lines and discuss the implications of our findings with respect to haptic feedback design, and device complexity.**

***Index Terms*—mid-air haptics, direction recognition, apparent tactile motion, tactile illusions, perception, haptic icons.**

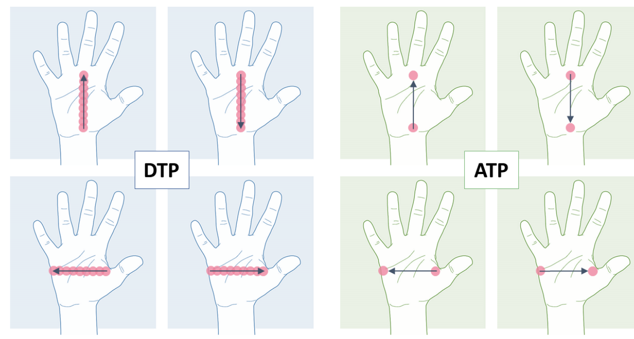

Fig. 1: *Left:* A mid-air dynamic tactile pointer (DTP) stimulates the palm in NWSE directions. Here, a single focal point moves smoothly but swiftly across the palm. *Right:* A mid-air apparent tactile pointer (ATP) stimulates the palm in NWSE directions. Here, a single focal point jumps from one side to the other.

I. Introduction

OVER the last few years, there have been substantial research efforts on advancing mid-air haptic technology [1], [2], [3], and specifically on how it could best deliver haptic-feedback to a variety of touchless human computer interfaces and applications (see recent review [4]). On the haptic rendering side of things, Long et al. demonstrated how it was possible to haptically render volumetric shapes onto a user's palm [5]; Frier et al. studied the optimal speed for spatio-temporal modulated signals to deliver haptic stimuli that feel stronger [6]; Hasegawa et al. reviewed of the different modulations [7]. On the hardware side of things, Morales et al. described an open platform for ultrasound phased arrays [8]; Marzo described the various components and challenges associated with building mid-air haptic prototypes [9]; Inoue et al. reviewed how one could scale these platforms up to large, modular, and distributed multi-unit settings [10].

Despite these technological advancements, we argue that there is much untapped potential in mid-air haptics if only we could better understand the perceptual properties and space of this tactile modality. For instance, Hajas et al. recently showed how using existing rendering algorithms and hardware, one could leverage chunking [11] to improve peoples ability to correctly recognise the displayed 2D shapes by over 30% [12]. Similarly, Pittera et al. showed how, using existing rendering algorithms and hardware, one could leverage the apparent tactile motion (ATM) illusion to induce the sensation of movement from one hand to the other, even though they were not connected [13]. Motivated by this, and the success of using tactile illusions [14] to design simplified yet effective haptic displays, in this paper we systematically show how using existing rendering algorithms and hardware, one can improve the recognition of tactile direction and simplify the rendering of smooth tactile motion. Namely, through two pilot studies, and one psychophysical user study involving 35 participants in total we have explored the temporal and directional parameter space of mid-air haptic line sensations, and also exploited the ATM illusion to optimise and simplify how these can be rendered onto people's palms using just their two end-points (see Fig. 1). By comparing continuous movement and apparent motion of mid-air tactile stimuli, the main contribution of the paper concludes that the two rendering techniques are perceptually similar.

Our results have far-reaching implications for both mid-air haptic rendering algorithms and hardware design. For example, they could be directly applied to enhance the works of Hajas et al. for mid-air haptic shape recognition [12], and also the works by Brown et al., for mid-air haptic icons in car human-machine interfaces [15], [16]. Importantly, the possibility to effectively render mid-air haptic lines (and geometric shapes made by lines) with just a few haptic points suggests that mid-air haptic devices may have been massively over-engineered and complexified. Simplified hardware designs and acoustic solvers running on cheaper microelectronics could potentially deliver comparable tactile sensations.

In Sec. II we motivate our study and present the relevant related works. In Sec. III we describe the study setup and apparatus that was used during the two pilots and main user study (see Fig. 3). In Sec. IV we describe our first pilot study where we investigate how the stimulus duration of a

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directional line sensation influences its recognisability. We call this stimulus dynamic tactile pointer (DTP). In Sec. V we describe our second pilot study, where we investigated how a smooth ATM can be effectively induced by appropriately sequencing the tactile display of just the end-points of the line. We call this stimulus an *apparent tactile pointer* (ATP). In Sec. VI we describe our main user study where we compared optimal line sensations delivered by a DTP against optimal ATM lines rendered by an ATP and show that there is little perceptual difference. In Sec. VII we discuss the implications of our results in terms of guidelines for UX designers and researchers, while accounting for some limitations of our study. Finally, in Sec. VIII we present the conclusions of our work.

II. Background and Related Work

A. Mid-air haptics and its modulation techniques

Ultrasonic mid-air haptic technology allows for creating a tactile sensation in mid-air without the need for body attachments, e.g., wearables, or hand-held controllers. It generally exploits a control algorithm that manipulates the amplitudes and phases of ultrasound waves emanating from an array of ultrasound transducers (usually operating at 40 kHz) to manipulate the resulting acoustic field. In doing so, it is possible to accurately synchronise and focus the wavefronts from each transducer to a desired position in space and time, creating a focal point (FP). The high intensity FP can be modulated in space and/or time to induce a vibrotactile sensations when touched.

In the literature, we can find a plethora of modulation techniques resulting in different vibrotactile sensations, each of which is more/less suitable for different purposes. Amplitude Modulation (AM) [1] refers to the case where the FP intensity is rapidly alternated on/off at frequencies of approximately 200 Hz to better stimulate the human tactile receptors. Lateral Modulation (LM) [17] or Spatiotemporal Modulation (STM) [6] keep the FP intensity constant and move it rapidly in space either oscillating laterally across a short distance on the skin of the order of a wavelength ($\lambda \approx 8$ mm) in the case of LM, or along a longer path to trace out the outline of a shape in the case of STM. Importantly, different modulation techniques have different device requirements. For example, AM requires a sinusoidal driving signal since a square wave would contain audible harmonics. STM and LM are even more demanding, as they require high sampling rates and phase depths so that the FP can be placed and moved rapidly and accurately along its intended path on the skin. These requirements often translate to more complex electronics and more computationally demanding operations, as recently presented by Matsubayashi et al. [18]. Another fundamental constraint of array focusing is the acoustic formation of grating lobes [19], which can be mitigated by non-lattice transducer arrangements, as demonstrated by Price et al. [20]. Finally, physical limitations due to energy dissipation, transducer directivity, and non-linear acoustics impose a law of diminishing returns for larger and larger mid-air haptic devices [10].

Smaller devices and simpler modulation techniques have been proposed and demonstrated. Morales et al. have built a small array comprised of concentric transducer rings capable of producing a static FP and parametric audio when driven by simple, single channel, electronics [21]. Hajas et al. proposed to slowly move an AM FP along the path of a shape to deliver a more perceivable stimulation [12]. This process takes the name of dynamic tactile pointer (DTP). Moreover, they proposed that the FP would make short pauses at the corners (or other salient features) of the presented shapes, thereby facilitating for the cognitive chunking of each of the multiple brush strokes needed to draw or trace out the 2D geometric shape [11]. For example, a square shape presented by this technique would comprise four brush strokes, whereby the FP is amplitude modulated and also moved along the four sides of the square while making a short pause at each corner. The resulting shape recognition was about 30% better than an STM square, while the computational and device requirements needed are significantly reduced.

In this paper, we present a parametric study of the DTP approach to enhance users' perception of dynamic stimuli. Namely, we will study how the duration of a single brush stroke affects the recognisability of its direction.

B. Apparent tactile motion illusion

The study of the ATM phenomenon has a very long history [22], [23], [24], [25], [26]. Those pioneering studies concluded how the illusion is based on the relationship between the duration of a stimulus and the stimulus onset asynchrony (SOA), i.e., the time between the onset of one stimulus and the onset of the following stimulus at a different location on the body. As illustrated in Fig. 2, if one keeps constant the haptic stimulus duration T of the two stimuli, then there are three possible SOA scenarios. In the first (Fig. 2.a), the SOA is too short, and the two haptic stimuli are merged at the perceptual level into a single percept, at a third location, possibly approximating the mid-point of the stimuli. In the second case, the SOA is too long (Fig. 2.b) leading to the perception of two distinct stimuli at two distinct locations. Instead, if one correctly modulates the SOA, users will perceive a dynamic sensation moving from one stimulus location to the other one (Fig. 2.c).

The ATM illusion is a well-known perceptual phenomenon, and it has been extensively explored, including in the visual (e.g., two static light sources turning on and off at a certain frequency) [24], and audio modalities (e.g., consecutive sounds with different onset times) [27]. Researchers have also explored the ATM illusion on different parts of the body. Miyazaki et al. targeted the fingers [28], Lechelt et al. the forearm [29], and Israr et al. stimulated the back [30], [31]. The ATM has been further explored on non-contiguous parts of the body interconnected by a device [31], non-interconnected by a device [32], and non-interconnected by a device and through the use of mid-air haptics [13]. Finally, Morisaki et al. [33] studied a similar apparent motion using ultrasound mid-air haptics, whereby an illusory tactile sensation is perceived near the midpoint of two adjacent tactile points (see Ref [34] for more details). In their work, they contrasted LM vs. AM generated pointers ATPs that smoothly switch their amplitudes between two positions on the palm and showed that AM was more effective in being perceived as a continuous motion.

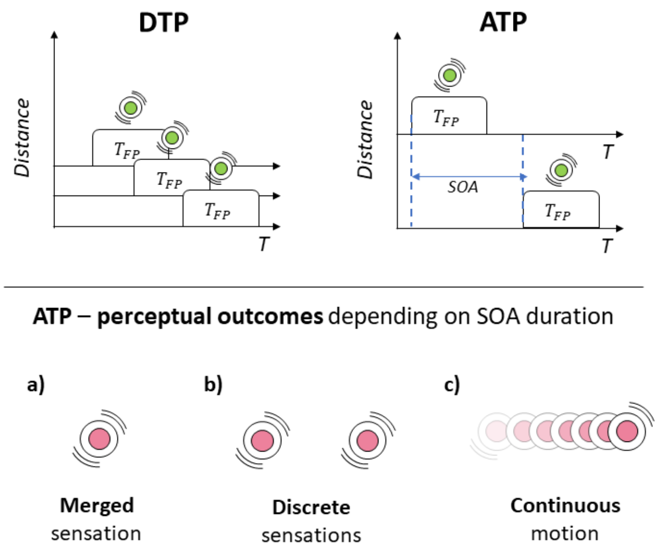

Fig. 2: The apparent tactile motion (ATM) illusion, specifically adapted to mid-air haptic line sensations. Top left: A tactile stimulus of duration τ_{FP} is moved along a certain skin distance within a time duration T at a constant speed $distance/T$. This is equivalent to the DTP mid-air haptic technique. Top right: A tactile stimulus jumps between two locations separated by a distance. The jump-time is defined as Stimulus Onset Asynchrony (SOA), that is, the activation time between the first and the second stimuli. In this case, changing the SOA duration will lead to three different percepts: a) the two stimuli are merged in a single illusory point. b) The two stimuli are perceived as separated/discrete. c) When the SOA is just right, the illusion is successful; a smooth sensation of movement between the two points is perceived. We refer to this as the ATP mid-air haptic technique.

In this paper, we explore if and how the ATM illusion can be leveraged to provide dynamic mid-air haptic information to an otherwise static FP that jumps from one side of the user's palm to the other, i.e., the endpoints of a DTP brush stroke. This could significantly simplify the computational and hardware requirements of the mid-air haptics display.

C. Motion detection

Tactile directional sensibility (i.e., the ability to perceive the direction of a moving stimulus) is based on two mechanisms responsible to retrieve the direction of motion: a) the friction sensitivity on the skin and b) the spatio-temporal information elaboration. Both these two processes seem associated with specific mechanoreceptors [35], [36], [37]. In particular, the SA-I mechanoreceptors (Merkel cells) appear more involved in the analysis of spatio-temporal signals, while the SA-II units (Ruffini corpuscles) seem more sensitive to lateral stretch of the skin [35], [36].

There have been several research efforts aimed at assessing the role of these two mechanisms in the tactile directional sensibility. Norrsell et al. found that the vertical load of the stimulus applied on the participants' forearm had the effect of increasing the performance in a directional sensitivity task [36]. This was true only in the case of a frictional stimulus (i.e., a metal tip). Instead, when the stimulus was an air-stream, the load-performance correlation was not found. Similarly, when they applied a surgical sticking plaster to limit the skin tractability, the performance deteriorated again. To support the thesis that the information gained from the skin stretch might be the dominant process used for discriminating the direction of a moving stimulus, Olausson et al. tested the participants' performance when a moving stimulus was applied on the forearm while resting the elbow in a straight position or with the elbow bent at 90 degrees to limit the skin suppleness. The authors demonstrated that the directional tactile sensibility decreased with the elbow bent at 90 degrees, equal to a 1/5 of the performance obtained while the elbow was maintained straight. Norrsell et al. also tested those two forearm conditions by using a non-frictional stimulus (i.e., air stream) observing no difference in participants' performance [38], thus confirming that for non-frictional stimuli we rely on processes other than the skin stretch information. Further, the stimulus load and the participants' performance were shown to be uncorrelated. It is worth noting that even in absence of skin stretch information, one can still retrieve details on the motion direction from spatial data expressed in function of time. The latter mechanism will, however, result in lower performance.

A recent study concerning an ultrasonic mid-air haptic stimulus was published by Perquin et al. [39]. In this study, the authors explored if participants could perceive the direction of a dot kinetogram stimulus (i.e., multiple points moving altogether in one direction) moving in a downwards, rightwards, and oblique downwards direction. The main objective was to explore if the tactile domain presented a similar directional bias effect as for vision. Indeed, the authors found that the participants' performance was better for vertical and horizontal stimuli compared to the oblique ones.

Finally, it is worth mentioning that the ability to recognise the direction of a moving stimulus is not the same as recognising that a stimulus is moving. This is clear from the clinical literature, in which it is possible to find patients that have only one of the two processes impaired [40]. Furthermore, the performance in a movement recognition task is higher than for a direction detection task [40], [36].

III. Experimental Apparatus

We utilised the same apparatus throughout the two pilot studies and for the user study. We used a 16 $\times$ 16 ultrasonic transducer array (Ultraleap Stratos Explore development kit) that produces 200 kPa of acoustic pressure and 10.89 mN of force at 20 cm distance [41]. The array was positioned inside a laser cut acrylic box. The top side was at 20 cm away from the array surface and presented an aperture of 13 $\times$ 13 cm to accommodate the participants' left palm. In the case a participant had a smaller hand, to facilitate the resting position, we applied a 3D printed square shape on the aperture to reduce it to 9.5 $\times$ 9.5 cm. Furthermore, to support the participants' forearm, we placed a cushioned armrest in front of the box containing the mid-air haptic device (see Fig. 3).

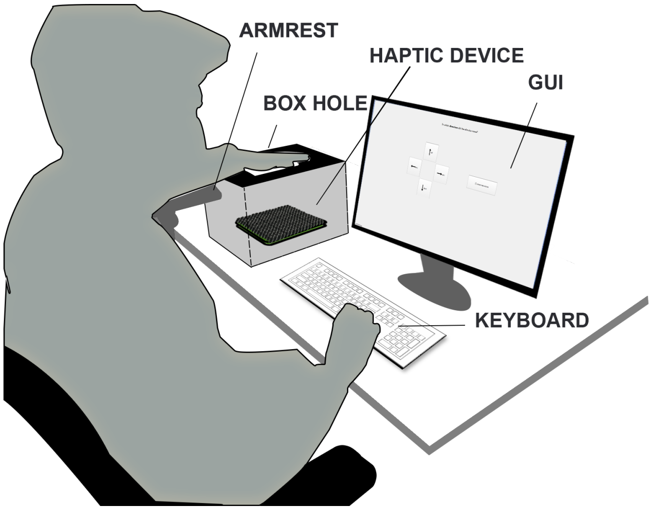

Fig. 3: Participants sat with their left arm on an armrest. Their left hand was lying on a 13 × 13 cm aperture on top of an acrylic box. The box contained an ultrasound haptic device to deliver the haptic stimuli. Participants were guided by the experiment GUI and could answer through a keyboard.

IV. Pilot 1: Parameters for motion detection

Through this first pilot study, we aimed to choose the duration $T \in [30, 240]$ ms of a stimulus moving along the four cardinal directions such that it is well perceived and correctly recognised. This parameter would later be used in Sec. VI for further investigations in our user study. The stimulus applied to all Pilot 1 participants was generated using the DTP approach, whereby an amplitude modulated FP is moved smoothly along the user's palm in the specified direction.

A. Participants

For this pilot study, we tested 10 participants (9 males, age $\mu = 30.6$, SD ± 4.82). They had normal or glasses/lens corrected vision and no history of neurological or psychological disorders. All participants were right-handed. Upon arrival, participants were asked to read the information sheet and sign a consent form before the task was explained in detail to them.

B. Procedure

After receiving the experiment instructions and before delivering the haptic stimulus, a researcher measured the participants' palm width (from the mid-point of the index finger bone to the mid-point of the little finger bone). The palm width values were recorded into the experiment GUI to allow scaling up or down the haptic sensation. Each participant sat comfortably on a chair with their left arm resting on an armrest as seen in Fig. 3, laying their left hand on the aperture of the box, thus exposing their palm to the haptic stimulus. The mid-air haptic stimulus was delivered by taking as a reference the centre of the participant's palm, and the length travelled by the sensation was equal to the measured length of the palm. Finally, all participants wore an ear defender headset (3M PELTOR Optime III Ear Defender, 35 dB) to isolate device and environmental noises.

The experimental session was preceded by a short calibration session to make sure participants were receiving the stimuli at the right location. First, a FP was delivered at (0,0,20) cm and the participants had to match their palm centre with it before moving to the training phase. In the training phase, a series of 10 stimuli, not part of the experimental phase, were delivered to the participant's palm. Each stimulus was preceded by an acoustic "*beep*" to inform the participants of the imminent start. After the stimulus was delivered, participants were prompted by the experiment GUI to answer two questions: 1) recognise the stimulus direction by pressing one of the four arrows on the keyboard to indicate the perceived direction (i.e., $\leftarrow, \rightarrow, \uparrow, \downarrow$), and 2) rate their answer's confidence level, from 1 (not at all confident) to 7 (very much confident). The 10 training phase stimuli presented had different durations: 40, 100, 200, 250, 300 ms, and directions: north, and east.

For this pilot study, we tested 32 different stimuli: four different directions, and eight different duration $T = \{30, 40, 54, 72, 98, 132, 178, 240\}$ ms. The stimuli duration range chosen was intended to include stimuli whose direction detection was at a not-perceivable and at a well-perceivable level, while also attempting to reduce as much as possible the stimulus duration. This was done with the anticipation of a possible future application employing multiple stimuli in motion (e.g., to form a 2D shape). Each mid-air haptic stimulus was delivered three times. In total, we presented to each participant 96 stimuli in a randomised order divided in three blocks of equal length.

C. Results

Psychometric curve: Fig. 4 shows the resulting psychometric curve fitting obtained from the 10 participants tested averaged over all four directions. On the abscissa are the tested stimuli durations, and on the ordinate axis there is the participants' performance expressed as the probability of perceiving the motion direction correctly. The vertical line represents the 80% threshold level. We note that the performance of the grouped directions never reached 100%. This means that even for the longest duration considered (i.e., 240 ms), it was impossible for all the participants to distinguish the correct motion direction 100% of the time. When considering each direction individually, we found that only the north direction reached the 100% performance. The threshold illustrated in Fig. 4 indicates that when the stimulus' duration is equal to 120 ms, participants were able to correctly discriminate the stimulus direction 80% of the times on average. Finally, it is possible to see that the performance was above chance level, and around 42% for the shortest stimulus (30 ms). For this reason, in Pilot 2 and in the final user study we changed the stimuli duration range, from 30 to 240 ms, to 15 to 240 ms. Doing this will include the full range of direction detectability. Furthermore, as the 15 ms stimulus is very rapid and could be confused with a static FP, in the user study we added 12 catch trials represented by static FPs (see Section VI for further information) to investigate if this could be the case. Further analysis of the 80% threshold grouped by direction shows that

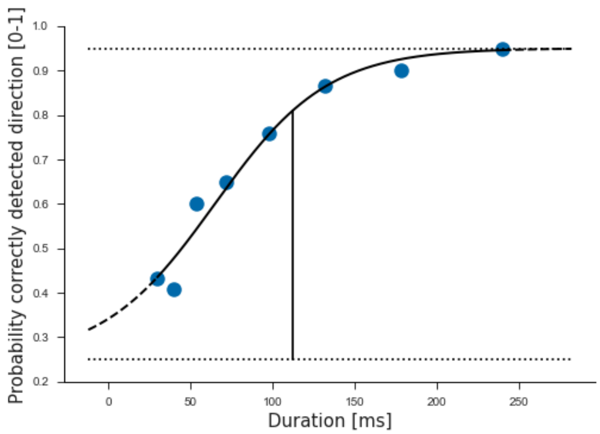

Fig. 4: Psychometric curve plot for averaged data collected in pilot study 1.

The curve shows the participants' performance in discriminating the motion direction (ordinate) depending on the stimulus' duration (abscissa). The vertical line represents the 80% threshold level.

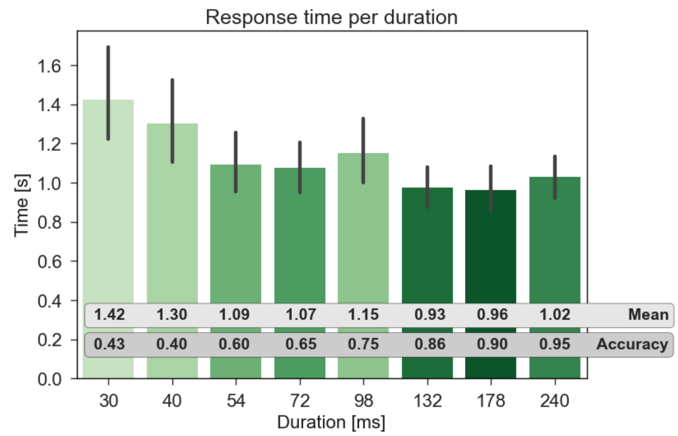

Fig. 5: Participants response time for pilot study 1. The greener the bar, the less response time. The error bars represent the 95% confidence interval.

the north direction had the lowest threshold of all the directions tested (i.e., the best performance).

Performance: when analysing the participants' performance, we observed that it increased with increasing stimuli duration and had an average accuracy level of 70%. For durations of 10 ms, participants made several mistakes, with an accuracy level of 43%. In particular, participants confused the direction pairs north-south and west-east. Indeed, when grouping our data by the two axis north-south and west-east, the accuracy level increases from 70% to 85%. This means that participants are generally good at understanding the orientation of the motion, but for fast stimuli, they struggle to correctly distinguish the stimulus' direction. For durations = 240 ms, the errors decreased drastically, with an accuracy level equal to 95%.

Duration Confidence levels correlation: When we investigated the correlation between the confidence levels and the stimuli duration (Spearman rank correlation test), we found a strong significant positive correlation ($r_s = 0.58, p < 0.001$)..

Response times: we visually explored the response times for the grouped stimulus' durations considered (Fig. 5). In the bar plot, we reported the mean values for each stimulus duration considered with its associated accuracy. The best performances are represented by a darker green colour. From the graph, it appears that the 178 ms and the 132 ms stimuli were the faster to be identified (considering also their level of accuracy), although a Mann-Whitney U test did not highlight any difference between groups.

V. Pilot 2: Apparent tactile pointer parameters

Through this second pilot study, we aimed to find the optimal parameters for the SOA (i.e., the time gap between the onsets of the two stimuli) that provides an effective apparent tactile motion (i.e., illusion of smooth motion). We therefore chose just one direction (West), and delivered a stimulus formed by a single FP that jumps across the end-points of the horizontal line, thereby physically only stimulating the start and finish locations of the analogous stimulus presented in Pilot 1 (see Fig. 1). We refer to this modified stimulus as the apparent tactile pointer (ATP) approach and investigate 9 different total stimulus durations $T = \{15, 30, 40, 54, 72, 98, 132, 178, 240\}$ ms while also adjusting the SOA (i.e., the onset jump time between FP locations). Specifically, we define the jump time τ_{SOA} and the stimulus duration at each end-point τ_{FP} through the equations:

$$\tau_{\text{SOA}} = (1+f)T/2, \qquad \tau_{\text{FP}} = (1-f)T/2 \tag{1}$$

such that $\tau_{\text{SOA}} + \tau_{\text{FP}} = T$, and $\tau_{\text{SOA}} - \tau_{\text{FP}} = fT$ is the gap duration, as can be seen from Fig. 2. Therefore, varying the adjustment factor (i.e., SOA factor), $-1 < f < 1$, it is possible to simultaneously linearly increase or decrease τ_{SOA}, τ_{FP} and fT, while not affecting the total stimulus duration T that remains constant.

Note that for $f = 0$ the two stimuli are exactly sequenced, and when $f > 0$ there is a gap. We did not study the case where $f < 0$ due to constraints in the device SDK (i.e., we cannot render two FPs at the same time).

For the purpose of our pilot study, we delivered FPs that jump from left to right on the user's palm, with SOA factors $f = 0.43, 0.25, 0.11$ and 0. With this range of values we investigated the case of no gap between the stimuli, a gap that is longer than the individual stimuli duration, and two values that make the gap less than the individual stimuli durations. We pre-tested factors $f > 0.43$ that resulted in clearly discrete FPs, hence, we excluded those values to keep the pilot study brief. In this pilot study, participants received a total of 4 (SOA_factors) × 9 (durations) × 3 (repetitions) = 36 trials, in a randomised order. Each study lasted approximately 10 minutes.

Results from this Pilot study will be used in the user study described in Sec. VI to compare participants' performance

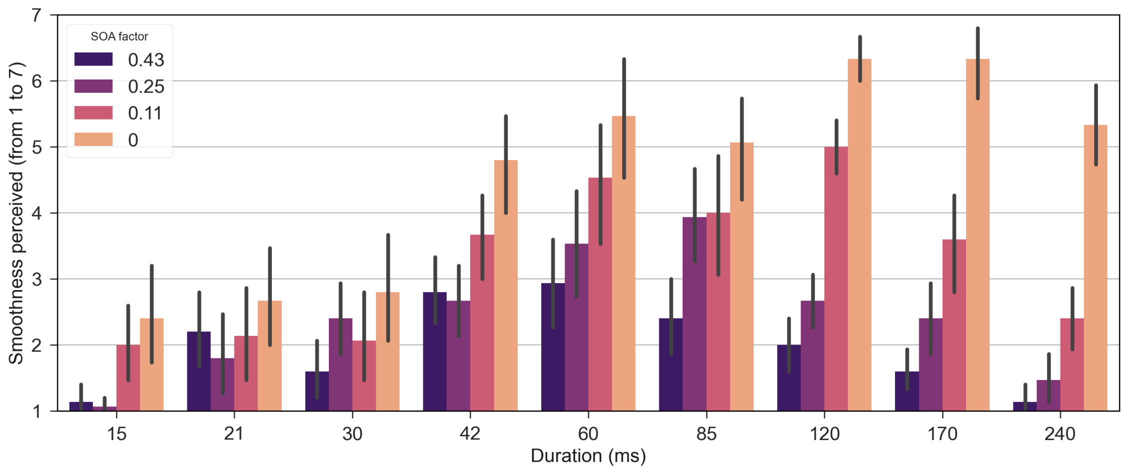

Fig. 6: Participants' ratings for smoothness of motion (from 1 to 7) grouped for each of the 9 different stimulus' durations and 4 different SOA factors f (f=0, means the stimuli are presented consecutively). A rating of seven means that the two FPs felt as a continuous motion, whilst a rating of one means the two FPs were perceived as discrete stimuli. The error bars represent the 95% confidence interval.

in a direction recognition task against the traditional DTP technique studied in Pilot 1.

A. Participants

For this second pilot, we tested five participants (4 males, age $\mu = 31.4$, SD ± 3.78). They had normal or glasses/lens corrected vision and no history of neurological or psychological disorders. All participants were right-handed. Upon arrival, participants were asked to read the information sheet and sign a consent form before the task was explained to them.

B. Procedure

The procedure for Pilot 2 was almost identical to Pilot 1 and used the same apparatus shown in Fig. 3. The experiment started after the calibration phase (with no training phase) during which a participant would be presented with an ATP, i.e., a FP stimulus that jumps from the left to the right end-point of an imaginary line on their palm. Each trial was preceded by an acoustic "*beep*" to inform the participants of the imminent start. After the stimulus was delivered, participants were promoted by the experiment GUI rate the perceived smoothness of motion from 1 (discrete motion) to 7 (continuous motion) using the keyboard. A 7 meant that they perceived the two FP locations as one point moving smoothly from left to right. A 1 meant that they could feel the two FPs as separate vibrations, one on the left part of the palm, and the other one on the right part of the palm.

C. Results

Fig. 6 shows the bar plot of the participants' ratings for the smoothness of motion, grouped for the different total stimulus durations T and different SOA factors f. Ratings approaching seven, means that the ATP was perceived more as a single FP moving continuously along a line from left to right and that the ATM illusion was successful. Ratings towards the other end of the scale, meant that the FP stimulus was perceived as two separate stimuli vibrating at separate times on the two spots of the palm.

For our final user study, we decided to consider only the case where $f = 0$, as this was the value that was always judged to render the most continuous motion for each of the nine stimuli durations. This means that when the FP jump-time τ_{SOA} was minimized, the participants perceived a smooth moving stimulus. Indeed, when we revealed to the participants that the stimuli they felt were rendered by two static FPs, they stated they thought it was a mixture of static and moving FPs (depending on the SOA factor f applied).

VI. User study: DTP vs ATP tactile directional sensitivity

Taking on board all the insights garnered from pilot studies 1 and 2, in this user study we aimed to: 1) identify the DTP parameters that improve the accuracy and speed with which a direction recognition task can be completed (similar to pilot 1), and 2) whether the much simpler ATP approach can produce a comparable performance as DTP. To that end, we designed a within-subject experiment where a new pool of participants experienced both DTP and ATP conditions, with varying total time durations T, and NWSE directions. Further, we recorded direction recognition answers, confidence levels, and response times.

A. Participants

For this user study, we tested a total of 20 participants (5 females, age $\mu = 30.25$, SD $\pm$ 6.74). They had normal or glasses/lens corrected vision and no history of neurological or psychological disorders. All participants were right-handed.

B. Conditions and stimuli

This user study was composed of two conditions. Condition 1 (DTP) involved a FP moving smoothly along the four

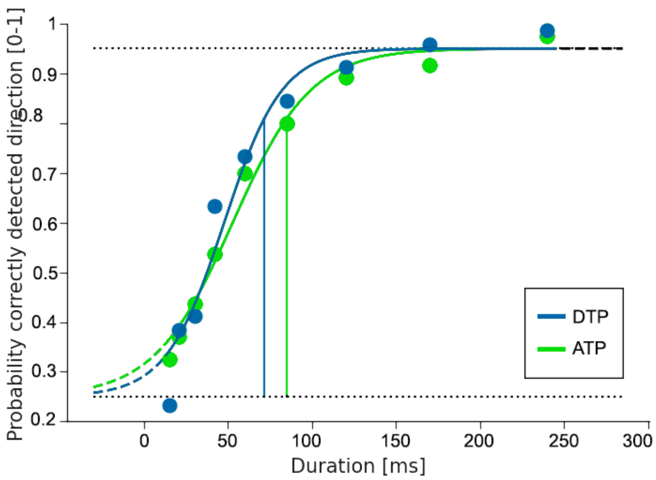

Fig. 7: *Blue:* Psychometric curve for the DTP condition, obtained from averaged data. *Green:* Psychometric curve for the ATP condition, obtained from averaged data. The two curves represent the performance expressed as the probability of correctly detecting the stimulus' direction (y-axis) varying with the increase of the stimulus duration (x-axis). The vertical lines represent the 80% threshold. As expected, the performance increases with the increase of the stimulus duration.

	80% Threshold (ms)	
Direction	DTP	ATP
NORTH	46.58	58.90
SOUTH	67.45	68.79
WEST	72.70	101.98
EAST	70.40	81.76

Table I: Values in ms corresponding to the 80% thresholds for the DTP and ATP conditions, obtained by averaging the participants' individual thresholds.

NWSE directions across the participants' palm. Condition 2 (ATP) involved a FP jumping across the four NWSE directions on the participants' palm with zero jump-time (i.e., $\tau_{\text{SOA}} = 0$). Conditions 1 and 2 are shown in Fig. 1. Both conditions were presented with nine different total durations $T = \{15, 21, 30, 42, 60, 85, 120, 170, 240\}$ ms, as in the previous Pilot studies. Each mid-air haptic stimulus was repeated three times. Finally, to measure the participants' guessing rate, we introduced 12 catch trials. These consisted of a 30 ms static FP delivered at a random point between 0-40 mm from the edge of the line moving along the four cardinal axes. This random delivery point was chosen to avoid participants from easily detecting the catch trial. In total, we presented $4 \times 9 \times 3 + 12 = 120$ stimuli, presented in three blocks, for each of the 2 conditions in a randomised order between participants. Finally, the order of appearance of the conditions was counterbalanced between participants, so that 10 participants experienced the DTP first, and 10 participants experienced the ATP first.

C. Procedure

The user study procedure was almost identical to Pilot 1. After the calibration phase, a training phase presented the participants with a series of 10 stimuli, not part of the experimental phase. These had durations $T = \{40, 100, 200, 250, 300\}$ in the north and east directions, and were either DTP or ATP, depending on what the start condition of the experiment was going to be. Each of these stimuli were preceded by an acoustic "*beep*" to inform the participants of the imminent stimulus. After the stimulus was delivered, participants had to press one of the four arrows on the keyboard to indicate the perceived direction (i.e., $\leftarrow, \rightarrow, \uparrow, \downarrow$) or press the "Delete" key, if no motion was perceived (i.e., during a catch trial). All the participants were instructed to keep their right hand on a fixed spot under the keyboard's arrows to standardise the time to reach the keys between participants. After that, they had to rate how confident they were in their answer, from 1 (not at all) to 7 (very much). The software would proceed to the experimental phase once the participant would correctly detect the FP direction for at least 80% of the times. Otherwise, the training phase was repeated until the threshold was reached. None of the participants had to repeat the training session.

During the experimental phase, participants were tested on the stimuli described in Sec. VI-B. The procedure was identical to that of the training phase. We recorded the stimuli perceived direction and confidence levels from 1 to 7 associated with the ratings. Further, we recorded participants' response time in selecting the stimuli direction. To make sure the response time was not influenced by the current location of the hand, participants were instructed to rest their hand on a mark near the keyboard arrows.

The experiment lasted approximately 40 minutes, and the participants were compensated with a £10 Amazon voucher. For this experiment, we sought and obtained ethical approval by the ethics committee at Ultraleap by following the GDPR regulations and according to the Declaration of Helsinki.

D. Results

Psychometric curves: We grouped participants' data by conditions (i.e., DTP vs. ATP) and proceeded to extract the two psychometric curves summarising participants' performances as seen in Fig. 7. To assess the goodness of fit, we used the bootstrap procedure implemented in the Quickpsy package for R (v4.4.2) to evaluate the deviance. We used the parameters of the fit to generate 5000 samples of data, and for each bootstrap sample we calculated the deviance of fits. Using the distribution of bootstrapped deviances, the probability of obtaining a value of deviance greater than that of the original data was calculated. No significant deviations were detected. The accuracy for the DTP and the ATP conditions were respectively 68% and 66%. We calculated the individual 80% thresholds for each participant for the two conditions, and then averaged them. For the DTP technique the threshold sits at 72.36 ms, 95% CI [66.74, 78.63], and for the ATP, the threshold is equal to 85.71 ms, 95% CI [78.39, 93.84] respectively. Table I reports the 80% threshold values in ms broken down for each direction.

In order to compare participants' direction discrimination performance for the two conditions tested, we calculated the

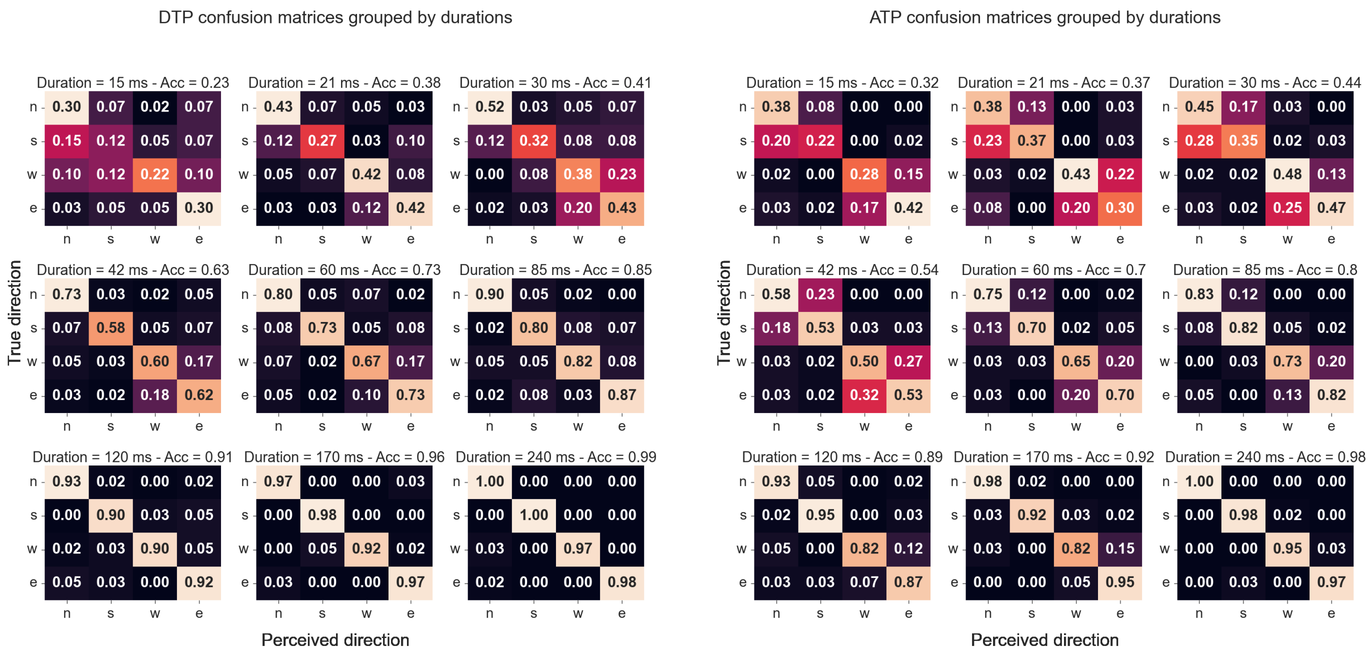

Fig. 8: *Left:* confusion matrices for the DTP condition. *Right:* confusion matrices for the ATP condition. At the top of the matrices, we reported the direction detection accuracy. The values in the cells represent the proportion of correct answers (0-1).

d prime, a measure of sensitivity derived from signal detection theory that is unaffected by response biases [42], [43].

An *a priori* power analysis was conducted using G*Power version 3.1.9.7 [44] to determine the minimum sample size required to test the study hypothesis. Results indicated the required sample size to achieve 90% power for detecting a large effect, at a significance criterion of α = 0.05, was N = 19 for a linear regression model. Thus, the obtained sample size of N = 20 was deemed adequate to test the study hypothesis.

In order to investigate the effects of our three independent variables (technique, duration, and direction) on the participants performance (d primes), we used the R stats4 package (4.2.2) to fit a multiple linear regression model by including a combination of the independent variables and their interactions. From the ANOVA and summary tables, all the interactions between the variables considered were not significant (0.09 < p < 0.96) and the only significant variables were duration and direction. The total variance explained by the model was 44.9%. We then excluded the technique from our model. We had a few significant interactions between the duration and the direction of the FP movement. In particular, for durations of 42 ms to 240 ms, the south direction had a significant relationship with the performance (0.01 < p < 0.04). The R^2 is equal to 0.454.

As we found only a few significant interactions of directions, we tried to consider only duration as a variable to understand participants' performance. Further, we compared the performance of the two models. The adjusted R^2 for the simpler model is 0.449 against the 0.456 of the model considering also direction. The Bayesian information criterion (BIC) for the simpler model is 2941.8 against 2944.3. Hence, it seems that the model considering only the duration could be sufficient to explain most of the variability in our data.

Finally, we extracted the Bayes Factor (BF) when comparing the two models. To interpret the BF, we used the proposed interpretations from [45]. When we compared model 1 (duration) with model 2 (duration and direction), we obtained a BF = 0.29, indicating a moderate evidence in favour of H0 (there is no difference between the models).

Next, we investigated the performance differences between the different stimuli directions within conditions. Both our data sets were likely to follow a normal distribution, hence, we performed two repeated measures ANOVA. For the DTP data, the ANOVA highlighted significant differences, $F(3, 57) = 2.99, p = 0.03, \eta^2 = 0.14$ (high effect size). We then proceeded with a Bonferroni corrected post-hocs t-tests that failed to highlight any significant difference ($p > 0.05$) pairwise. For the ATP, there were no significant differences ($p > 0.05$).

Finally, we checked the performance differences between the two conditions when grouping the data by stimuli durations. This time, both distributions were not normally distributed, hence, we performed two Friedman tests. For the DTP, we found significant differences: $\chi^2(8) = 134.11, p < 0.001$ with a large effect size $W = 0.83$. We proceeded with post-hoc Wilcoxon tests, and we found that all the pairwise comparisons were statistically different except for pairs 21-30 ms, 120-170 ms, and 170-240 ms. The longer duration was obtaining better performances. For the ATP, we also found significant differences: $\chi^2(8) = 133.59, p < 0.001$ with a large effect size $W = 0.83$. In this case, Wilcoxon tests on the durations were always significant except for the pairs: 15-21 ms, 21-30 ms, 30-42 ms, 60-85 ms, 120-170 ms. Again, longer durations corresponded to better performances.

Confusion matrices: We report the confusion matrices (which exclude the "no motion" answers) for the different

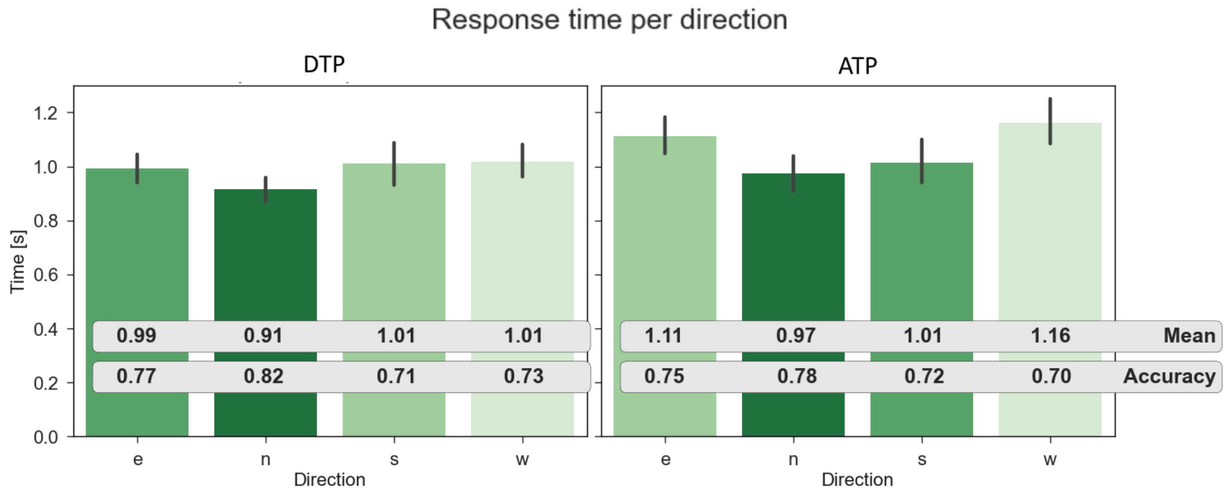

Fig. 9: *Left:* DTP grouped response times for each direction. *Right:* ATP, grouped response times for each direction. In both cases, greener colours correspond to slower response times. For both techniques, it seems that the North direction was the quickest direction to be detected. The error bars represent the 95% confidence interval.

stimuli durations with their accuracy levels, for both conditions in Fig. 8. Overall, the confusion matrices confirm that the north direction (bottom to top motion) was the most recognised direction. The accuracy levels for the two conditions appear comparable. As expected, most of the errors lie on the directions belonging to the same axis. That is, the participants seem able to detect that a stimulus is moving along the vertical or the horizontal axes, but might not be able to precisely discriminate the direction of the stimulus depending on its speed. Indeed, if we group the stimuli by their axes, the accuracy levels for the DTP and the ATP conditions increase from 68% and 66% to 75% and 80%, respectively.

Response time: Fig. 9 shows the response times for the grouped stimulus' durations considered with the corresponding accuracy. In both conditions, the north direction appears to be the one requiring less elaboration time to be detected. Nevertheless, our model did not highlight a significant effect of the north direction, and the effect might be a bias response of the participants.

Catch trials: The user study included a total of 24 catch trials, 12 for each condition. These, were static FP presented for 30 ms near one of the end-points of a randomly selected cardinal direction. We analysed the participants' response rate to the catch trials (i.e., how many times participants answered there was movement even if the FP was static) to investigate their guessing rate and their accuracy level (i.e., if motion was perceived during a catch trial, how many times did participants correctly identify the end point direction). For the DTP condition, the response rate was 47.9% with an accuracy level of 75.7%, while for the ATP condition the response rate was 43.4% and the accuracy level was 75%.

VII. Discussion and mid-air haptics design implications

In this paper, we presented a user study aimed to assess participants' ability to discriminate the direction of a stimulus in motion, either by physically moving a mid-air FP or by exploiting the apparent tactile motion illusion.

A. Summary of results and their implications

In this paper, we have studied: 1) how mid-air haptic direction recognition is affected by the duration of a moving DTP stimulus along the four NWSE directions on the palm, and 2) if the ATM illusion could be leveraged to produce an ATP sensation that performs similarly to the former in terms of direction recognisability. Below, we summarise our main results and reflect on their implications for mid-air haptic designers and researchers.

- DTP and ATP techniques offer comparable direction recognisably, reaching 80% at $\sim$ 80 ms stimulus durations and improved further for longer stimuli.
- Both DTP and ATP are better recognised in the case of directional sensations that move from the bottom to the top of the palm (i.e., north direction). This is in line with previous literature that found a preference for the vertical motion when using multiple stimuli moving in the same direction (i.e., kinetograms) [39].
- Participants needed an average time of $\sim$ 1 second to be able to detect and input the stimuli direction into the experiment GUI.
- It appears that both, DTP and ATP, are recognised faster in the case of directional sensations that move from the bottom to the top of the palm (i.e., north direction), although our analysis failed to highlight a significant difference. This would be in line with previous literature that found a preference for the vertical motion when using multiple stimuli moving in the same direction (i.e., kinetograms) [39].

The above findings imply that when using a sequence of mid-air haptics lines to create a shape, e.g., a square, north lines can be rendered faster than others. This is an important design guideline for applications where a mid-air haptic stimulus and the information it conveys (e.g., confirmation feedback, function, direction, etc.) needs to be delivered quickly, e.g., in an automotive setting [46]. Moreover, the different recognisability times shown in Table I could be used as a constraint for the design of Ultrahapticons [46]. We remark that, if the application scope allows for it, discrimination of motion along the two axes, vertical and horizontal, would significantly improve the performances reported on herein since N-S and W-E direction pairs were often confused with each other.

The above findings also suggest that simplified hardware that is not able to render DTP sensations, either because of reduced signal processing capabilities or its transducer layout (e.g., see [21]), could instead leverage the ATM illusion and render ATP sensations without loss in performance. This is important in applications where cost and simple electronics are desired, e.g., in an elevator panel setting [47]. Here, an array of discrete FP locations can be multiplexed in time to produce perceptually dynamic tactile sensations.

We note that while increasing the stimulus' duration might help improve the motion detectability, it remains to be explored what is the threshold between detection of motion and perception of absence of motion (i.e., when a stimulus is very slow, it might be perceived as static).

B. Static FPs to convey directions

Participants tended to answer to almost 50% of the catch trials (see Sec VI-D for more detail). A catch trial involved a static FP that participants tried to interpret as the direction of a motion. This might well be because of the nature of the test. Participants were not aware of the presence of the catch trials, but they knew that they were supposed to detect the direction of a moving stimulus. It could be that they tried to interpret any bit of information as a cue to obtain the direction of motion. Further, participants' accuracy levels for the catch trials (i.e., correctly guessed the position of the catch trial on the palm intended as the last position of a supposed fast-moving point) were $\sim$75% for both techniques and higher than the corresponding 30 ms stimuli in motion (*DTP*: 41% - *ATM*: 44%). This is probably because interpreting a single FP as a cue for direction creates less confusion than interpreting one in motion passing through many locations or interpreting two FPs locations delivered in an ATM fashion. Moreover, the task of interpreting a single FP location, changes from being a temporal order judgment task to become a stimulus location task, which might rely on simpler neural and cognitive mechanisms. On the other hand, the response times for the catch trials were, on average, 210 ms higher than for the 30 ms in-motion stimuli in the DTP condition and 30 ms higher when compared to the ATP condition. We speculate that at a subconscious level, participants realised that something was different and had more uncertainty in their answers. Indeed, when checking the answers' confidence levels averages we found that in the DTP condition, the catch trials stand at 2.6 against the 30 ms stimuli at 3.16 (Mann-Whitney U=3354, p=0.004). For the ATP condition, the catch trials confidence levels were at 2.42, against 2.76 of the 30 ms stimuli (Mann-Whitney U=3497, p=0.041). Therefore, the confidence levels for stimuli of 30 ms actually in motion, in both conditions, were rated significantly higher than the 30 ms catch trials (static FPs). At this point, and with such high accuracy levels, one might suggest that a single static FP might substitute moving stimuli to convey motion direction. In conclusion, the participants answered about half of the time to the catch trials with high accuracy, probably because of the nature of the task's request, but the time to process the stimulus was higher. We think that for simpler applications that require the user to locate a single stimulus on the palm, it might be possible to implement static stimuli with a duration of 30 ms, and that accuracy level might be comparable to moving stimuli with longer durations of up to 60 ms.

C. Limitations and future works

Although our work offers useful guidelines to advise designers and engineers when using mid-air haptic stimuli in motion and an alternative method to convey a similar sensation, we also need to acknowledge some study limitations. Namely, we did not investigate the upper limit of a stimulus duration. This means that, while increasing the stimuli duration beyond the 240 ms limit discussed in this manuscript might improve participants' performance, we do not know the threshold between better perceiving the stimulus' direction and perceiving an absence of motion (i.e., the stimulus is so slow to appear static). Another limitation relies on the limited sample we analysed and its gender unbalance. Despite this, we believe our general results would hold, while the time responses and performance would probably vary when considering additional participants of different demographics. Another limitation relates to more complex stimuli composed by multiple DTP/ATP lines, such as 2D shapes and icons [48], or when mixing different AM frequencies, non-symmetric FP durations, and accelerated DTP lines (i.e., moving FPs at a not constant speed). Prior literature suggests that the ATM illusion generalises well [26], [49] however we have not studied all these possibilities and whether they may improve the recognition rates. Also, we might want to study if and how the results presented herein generalise to other body parts, such as the fingers [50] and the forearm [51].

VIII. Conclusion

In this paper, we have investigated two rendering techniques, DTP and ATP, to convey a perceivable detection of mid-air haptics stimuli direction. Through two pilot studies, we first obtained the optimal values to set our parameters for the DTP and the ATP conditions. In a final user study, we compared the two techniques and analysed some of the most useful factors (e.g., duration, direction, confidence, accuracy, and response time) that control how well we can convey a perceivable motion direction for stimuli $\leq$ 240 ms. Our study resulted in a set of design guidelines (see Sec. VII-A) that can be used by UX designers and practitioners when designing mid-air haptics for applications involving the need for direction detection (e.g., sat nav, icons, feature feedback, etc.). The guidelines include insights about what directions are most accurate and quick to be recognised while also how accuracy scales with duration (see psychometric curves in Fig. 7). For example, a stimulus moving from the bottom to the top of the user's palm was the best performing one, with an 80% recognition rate on average when the stimulus duration is just 59 ms and 78 ms for DTP and ATP, respectively. Further, we found that users will need $\sim$1 second after the stimulus to be able to perceive and input its direction. Finally, having shown that ATP has similar direction recognition performance to DTP, we have argued that depending on the application at hand, some mid-air haptic systems can be simplified in terms of their compute and acoustic field synthesis capabilities, thus reducing their build cost and operational complexity.

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