Dynamic pattern recognition with localised surface haptics and apparent motion

Mathilde Jeannin, Ayoub Ben Dhiab, Charles Hudin, Sabrina Paneels

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Mathilde Jeannin
Université Paris-Saclay
CEA, List
Palaiseau, France
mjajeannin@gmail.com

Ayoub Ben Dhiab
Université Paris-Saclay
CEA, List
Palaiseau, France
ayoub.ben-dhiab@cea.fr

Charles Hudin
Université Paris-Saclay
CEA, List
Palaiseau, France
charles.hudin@cea.fr

Sabrina Panëels
Université Paris-Saclay
CEA, List
Palaiseau, France
sabrina.paneels@cea.fr

***Abstract*—Surface haptics is gaining increasing interest due to the potential of the added tangibility to standard touchscreen devices, with compliance effects, different localised multitouch feedback or textures. Dynamic illusions provide further possibilities, such as apparent motion, to indicate directions or other more complex motions. It could also help feel the contours of a shape, particularly useful in the accessibility field for digital graphics. The confinement of vibrotactile stimuli is a recent method that enables not only to provide both localised and multitouch feedback but also to put the whole hand on the display. Thus, it has the potential to combine different interaction styles, from static to dynamic interaction, with a single finger to the whole hand. Yet, so far, there has been little work on tactile interactions, and particularly pattern recognition with this method. Therefore, this paper presents a preliminary investigation into the feasibility of using confined vibrotactile stimuli to identify geometric shapes using apparent motion. The results show that participants could feel continuous movements and with training reached recognition rates overall of 72.1%.**

***Index Terms*—localised haptics, confinement of vibrotactile stimuli, apparent motion, surface haptics, shape recognition**

I. Introduction

Surface haptics is gaining increasing interest in the recent years due to the possibility of adding enhanced haptic feedback [1] to common mobile displays such as smartphones, tablets or any screen displays such as in cars (e.g. demonstration of the interactive haptic screen of the Mercedes S Class at Eurohaptics'22). This feedback can be localised [2], [3] or textured [4] (refer to the review [1] for more examples). This enables to improve user experience [1], but also opens up new possibilities in the accessibility field thanks to the added tangibility [1], [5], [6]. In particular, by combining static and dynamic feedback, as well as leveraging haptic illusions [7], richer information can be conveyed. For instance, by combining position with force sensing, the illusion of compliance when pressing a button can be provided [8], [9]. Dynamic illusions also hold the potential to provide information about movement [7] (e.g. for movies or gaming [10], for musical performance [11] or to help feel directions for navigation [12]). Graphical information remains difficult to access by visually impaired people and surface haptics could improve such access, either with active exploration or by relying on haptic illusions and passive touch.

Providing tactile patterns and shapes has been well studied through arrays on the body, e.g. [13]–[16], to indicate directional cues in navigation tasks for instance. A few researchers have also started investigating conveying directional and shape patterns on surfaces for mobile devices application. However, they used either technologies with vibration propagation, preventing localised feedback or ones that are limited to active exploration. The confinement of vibrotactile stimuli method is relatively recent and enables both localised and multitouch feedback, as well as both passive and active exploration. By combining it with dynamic illusions, this technology further offers the possibility to convey continuous motions, from finger to hand interaction. However, work conducted so far with this method has mostly focused on the principles for localisation of feedback in both 1D [3] and 2D setups [17], with no studies on tactile interactions or pattern recognition. Therefore, this paper presents a preliminary investigation into the feasibility of conveying both linear and shape patterns with apparent motion using the confinement of vibrotactile stimuli.

II. State of the art

As described in Basdogan et al.'s review [1], work in surface haptics has mostly focused on vibrotactile or friction modulation feedback. In terms of conveying shape patterns, work has been conducted with both feedbacks.

For friction modulation, Xu et al. [18] have tested the active exploration of three types of shapes (square, circle and triangle) and three types of rendering strategies (solid, outline and solid with outline) with three visually impaired participants. They reached an overall recognition rate of 56%, reaching nearly 80% for solid shapes. Similarly, Sadia et al. [19] investigated the complexity of displayed geometry (i.e. number of edges) and the size of the haptically active area (i.e. with haptic rendering inside the shape, outside or on its edges), as well as the effects of orientation on the perception of five tactile shapes (triangle, square, pentagon, hexagon, and octagon) with electrovibration. They found that the recognition rate was inversely proportional to the complexity of the shape, with rates dropping significantly from more than five edges (from about 80-90% to 30%). The size of the haptically active area also had an impact on the perception of shape, with better results for larger areas such as in the feedback inside condition. However, friction modulation technologies cannot provide multitouch feedback and require active exploration. On the contrary, the method of confined vibrotactile stimuli enables multitouch surface feedback, both active and passive exploration, as well as feedback conveyed to the fingers or the whole hand. As mentioned by Sadia et al. [19], multitouch exploration is often preferred by visually impaired users. Thus, we thought it would be interesting to investigate the transmission of shapes passively with this method. Indeed, in some scenarios such as deafblind [20] or interpersonal communication, using the whole hand is important. Moreover, multitouch capabilities can enable more varied feedback, to different fingers or parts of the hand depending on the context.

For vibrotactile feedback, researchers have mostly investigated the use of apparent motion to convey directional patterns and shapes. Apparent motion is a type of haptic illusion [7] that involves the perception of a continuous movement or flow of a stimulus, through the sequential activation of discrete actuators. Hence, it is particularly relevant to convey dynamic patterns, such as directions or shapes. For instance, Seo and Choi [21], [22] introduced the concept of vibrotactile flow, defined as a "continuously moving sensation of vibrotactile stimulation applied by a few actuators directly onto the skin or through a rigid medium", and based on the illusion of apparent motion. They conducted several studies with two LRAs to characterise the design space of vibrotactile flows on a surface held by the hand (similarly to a smartphone). Their main results were that the control law for vibration rendering as well as signal duration had a significant impact on the perceptual characteristics of vibrotactile flows. In particular, they concluded that linear amplitude rendering and low velocity produced motions spanning a longer distance than log amplitude rendering and rapid velocity [21]. However, in terms of uniformity of perceived intensity, log amplitude rendering and fast velocity showed better performance than linear amplitude rendering with low velocity.

Kang et al. [23], [24] proposed a new method to generate smoother vibrotactile flows based on sweeping frequencies. They investigated the effect of frequency (constant or swept), amplitude (constant or modulated), signal ending (smooth or sharp), and different amplitude modulation methods (constant, linear, log and exponential) to determine the most effective parameters. They evaluated this on the mockup screen of a mobile device equipped with four piezoelectric actuators on the sides, as these provide a wide bandwidth and fast response time. Results showed that frequency, amplitude and ending point all significantly affected the seamless perception of the flow, with frequency being the most important factor [23]. The follow-up study [24] demonstrated that the exponential modulation of amplitude was the least accurate, clear, and smooth for perceiving vibrotactile flows on the palm, while other amplitude modulation methods produced similar results. To characterise the design space of vibrotactile flows in a systematic manner, Seo and Choi [22] proposed and evaluated a polynomial synthesis function for rendering vibrotactile flows with different degrees and different velocities and observed the impact on the sensation movement distance, velocity variation, intensity variation and confidence rating.

This previous work demonstrated that linear motions could be conveyed with as little as two actuators. With four actuators, Kang et al. [24] obtained recognition rates above 65% for eight directional flows (horizontal, vertical, diagonal), with better recognition for horizontal and vertical flows vs diagonal ones. However, their principle for generating vibrotactile flows does not enable localised multitouch feedback and does not provide the flexibility to set the frequency and amplitude of the actuators at any desired values for richer feedback. In addition, the generated motions were limited to 1D motions. Seo and Choi [25] extended their work with the concept of "edge flows", i.e. motion along the edges of a 2D surface, with four LRAs. They investigated the recognition of 32 different edge flows, with different starting edges, number of edges and directions, and evaluated the impact of training and correct-answer feedback over several days. The results highlighted the beneficial impact of repeated training as well as correct-answer feedback for identification. However, similarly, their work was also limited to linear motions and the impact of vibration propagation is unknown on the perception of the motion. Thus, this work not only investigates whether the same results are applicable with confined vibrotactile stimuli but also the recognition of more complex shapes.

Other researchers have investigated sparse arrays with the apparent motion illusion. Using a technique similar to amplitude modulation, Yatani and Truong [26] generated single point vibrations and vibration flows using five vibration motors embedded in the top, bottom, right, left, and center of a sleeve at the back of a mobile touch screen device. To avoid issues of hand contact with the actuators, they curved the sleeve to fit the shape of the user's hand when it holds the device. In their pattern recognition study, participants identified correctly the 11 patterns with a 89.6% accuracy on average. The patterns included the five single points, horizontal and vertical directions, and circular patterns (in both directions). Israr and Poupyrev [10], [27] investigated the control space of apparent motion, in particular stimulus onset asynchrony (SOA) thresholds based on different frequencies and durations as well as a model for phantom intensity. They used these results to combine both apparent motion and phantom illusions and to propose the Tactile Brush algorithm to produce 2D continuous vibrotactile strokes on the skin. However, this algorithm presented two limitations, the obligation to have linear paths between two actuators and issues regarding physical actuators overlap in activation sequence when having several phantom positions involving common physical actuators. Hence, Park et al. [27] proposed a rendering algorithm solving these issues to create smoother tactile strokes along arbitrary paths. Their user evaluation of half-circles and circles identification demonstrated the improved and more uniform perception of the target trajectory and was preferred over the Tactile Brush. This holds a lot of potential for complex shapes, yet the technologies used for evaluating these algorithms cannot be integrated into touchscreens as they rely on direct or close contact with the actuators, as opposed to the method of confined stimuli, which can be integrated with OLED screens. As the method is applicable to a 2D array of actuators [17], these algorithms could be investigated in follow-up work. However, this work aimed first at a preliminary investigation of the feasibility of using the method of confined stimuli with apparent motion.

III. Dynamic pattern recognition user study

The purpose of this preliminary study was thus to find out whether the apparent motion could be reproduced effectively with confined vibrotactile stimuli and whether it could be used to convey information such as geometric shapes. In particular, this study aimed to determine which patterns could be felt and recognised, as well as the impact of direction, orientation and shape complexity, if any, and training.

A. Protocol

1) Participants: Eight participants (3f-5m) were recruited from our laboratory, aged 21 to 28 (M = 24, SD = 2.3), amongst whom one participant was left handed. They had no known sensitivity or sensory disorders. They were familiar with surface haptics, but not the apparent motion illusion.

2) Setup: The experimental setup (see Fig. 1) was a rectangular plate of anodized aluminium (105 x 100 mm) fixed to a 3D-printed frame using epoxy. Eight 22 mm diameter piezoelectric actuators with a 35 mm scope between two consecutive actuators were glued manually at the back of this plate. This distance was chosen by keeping roughly the same proportions as used by Park et al. [27], who used smaller piezoelectric actuators in contact with the palm of the user. We hypothesised that the glued piezoelectric and their wires did not change the properties of the plate, as they do not change its rigidity and thus the propagation of waves. We chose anodized aluminium to isolate the participants from the piezoelectric actuators and to prevent them from any power stroke risks. Eight actuators were chosen due to technical limitations and as a suitable compromise between their size, number and the generated amplitude, impacting in turn the driving voltage and the corresponding driving electronics.

The boundary conditions of the plate were chosen to prevent the waves from propagating. To confine vibration on a 2D surface along both axis, only low frequency evanescent phenomena have to exist, which can be achieved using two properties: one based on the geometry of the propagation medium, the other on periodically placed supports. We thus integrated stiffeners to the structure in a periodic fashion (glued to the surface with epoxy) and formed three areas that took the shape of a waveguide. The bars were themselves fixed into the acrylic-glass support through pins. We designed the device so that the cut-off frequency reached $3\,\mathrm{kHz}$. As the tactile sensitivity is optimal around $250\,\mathrm{Hz}$, we were under the right conditions to observe the confinement of vibrotactile stimuli [17].

To characterise the plate's vibration amplitude, we used a basic sinusoidal signal without any window function. The generated vibrations were measured with a vibrometer, and

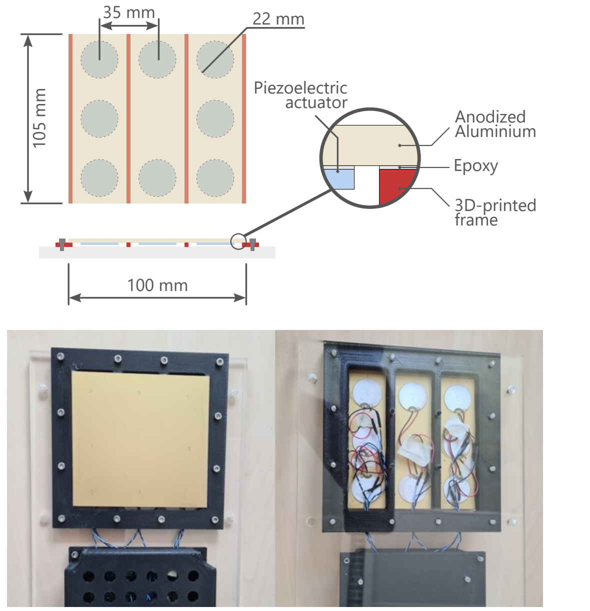

Fig. 1. Top: diagram of the setup, with its dimensions, layers and actuators layout. Bottom left: picture of the top view of the setup. Bottom right: picture of the bottom view with the piezoelectric actuators, the bars for the wave guides and the pins for fixations through the acrylic glass support.

varied between 17.7 µm to 21.7 µm (M = 19.6). This variability could be explained by the manual gluing process affecting the bonding of the piezo actuators to the plate.

3) Apparent motion illusion: There are two main ways to induce the apparent motion illusion: time or amplitude modulation. In this study, we opted for amplitude modulation based on the results of a pilot study involving four haptics experts, who found it to be more comfortable and clearer in terms of perception compared to time modulation. Future studies should also investigate the use of time modulation and compare the two types of modulation. The amplitude modulation followed a linear control law, as per Seo and Choi's results [22], [25]. An example of a triangular pattern from the activation of piezoelectric actuators 1 to 6 to 7 to 8 and back to 1 is illustrated in Fig. 2, as well as the amplitude control law that generated the illusion of motion through successive decreases and increases in amplitude between positions. The velocity of the movement was kept constant.

During preliminary tests, we realised that it was difficult to feel sharp corners such as for squares, and instead the change of direction felt smooth and hence more like a circle. Thus, to provide the illusion of a sharp corner, we added a longer pause ($0.15\,\mathrm{s}$, empirically and subjectively determined) at the corner before continuing with the movement, as exhibited on Fig. 2 with the plateaus at corners 1, 6 and 7.

4) Tasks: The study occurred over three consecutive days. The three days consisted each in a familiarisation, a training and a recognition task. We chose three days of training as Seo and Choi [25] demonstrated that training sessions were necessary to improve the recognition rates and that three days were enough.

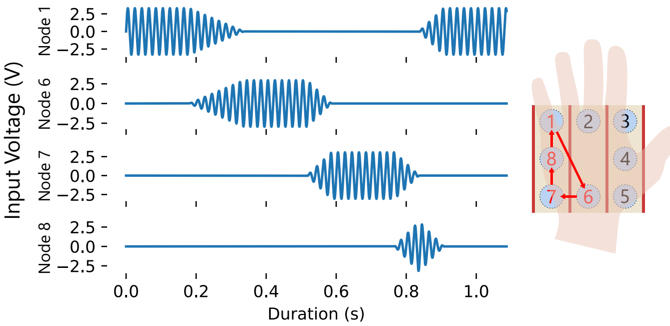

Fig. 2. Top: example of a triangular movement from actuator 1 to 6 to 7 to 8 and back to 1 again, with “pauses” at corners 1, 6 and 7. Bottom: corresponding input signals sent to the NI card (the frequency here is 50 Hz instead of 250 Hz for visibility of the sinusoidal signal).

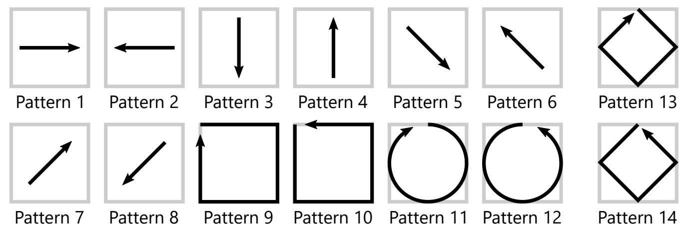

Fig. 3. Patterns of the experiment: horizontal, vertical and diagonal lines and complex shapes, i.e. circles and squares, and rotated squares in both directions.

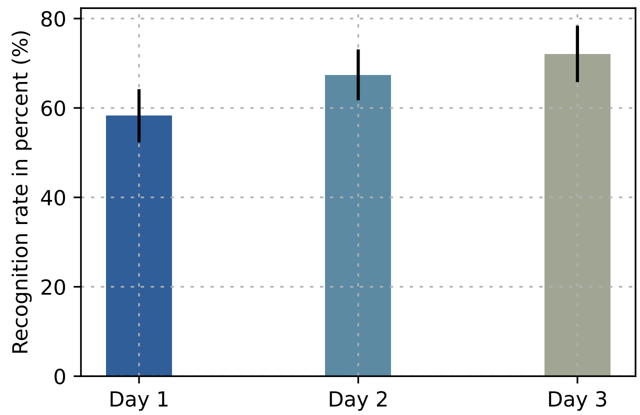

Fig. 4. Recognition rates along the three days averaged over the participants and patterns for each day, with 95% confidence interval.

As our pilot study highlighted that participants had different sensitivity and preferences for the velocity and frequency, we let these be user-determined for optimal identification, as a balance between comfort and performance with an ecological use case in mind. Thus, on the first day, participants were presented first with a triangular pattern (as in Fig. 2) with different velocities ranging from 150 to 300 $\mathrm{mm/s}$ and a fixed 250 Hz frequency at first. Once they chose their preferred velocity, the same pattern was sent with different frequencies ranging from 100 to 400 Hz until they chose their preferred frequency. These parameters were recorded for each participant and kept unchanged throughout the study. Participants chose velocities with a median of 250 $\mathrm{mm/s}$ (min 150 and max 300 $\mathrm{mm/s}$) and a frequency with a median of 250 Hz (min 200 Hz and max 400 Hz).

On the last day, after the recognition task, the patterns were sent again only once and randomly to the participants and they were asked to rate on a 5-point Likert scale (1-negative, 5-positive) the continuity of the movement, the fidelity compared to its visual representation, the perception difficulty for each shape and the impact of training.

In terms of tasks, during the familiarisation, participants felt each of the 14 patterns once with indication beforehand about what shape was presented (see Fig. 3). Then for the training task, they felt all the patterns three times in a random order (so 42 in total) and had to choose which pattern they felt verbally. They were not able to repeat the pattern. The GUI indicated all the 14 patterns all the time and displayed the right answer after the given choice, as Seo and Choi recommended (right answer feedback [25]). Answers during this training task were not recorded. After this training session, followed the main recognition task, where all 14 patterns were played four times in random order, so 56 times in total, and without the right answer feedback. In this task, similarly to the training, the participants had visual cues in the form of displayed figures on the GUI and they had to determine which pattern they felt and provide the answer verbally. Throughout the study, the participants put their palm on the plate to be in contact with as much surface as possible. They wore headphones with pink noise to avoid any bias due to the sound of the vibrations.

The 14 patterns evaluated are depicted in Fig. 3, including a line, a square and a circle with different directions and a different orientation for the square. For instance, patterns 11 and 12 both corresponded to a circle shape, but in clockwise or counter clockwise direction respectively. Patterns 13 and 14 were rotated squares in both directions to observe any impact of rotations on the recognition.

B. Results

1) Recognition: The success rates were above chance and as expected, there was an improvement over the days with 58.3%, 67.4%, 72.1% for day 1, 2 and 3 respectively, see Fig. 4. These results are similar to the ones obtained by Seo and Choi [25] in their study with a mean percentage of correct answers increasing from 52.5% on day 1 to 67.2% at the delayed recall test, close to the performance on day 3. A one-way repeated measures ANOVA showed that the performance was significantly affected by training, $F(2, 14) = 14.9$, $p < 0.05$. Post hoc tests with Bonferroni correction revealed that the difference was significant between day 1 and 3 ($p < 0.05$) but not between day 1 and 2 nor between day 3 and 2 ($p > 0.05$).

When analysing the tendency by category of patterns, the effect of training was more notable for complex shapes than for linear patterns, with a progress of 58.6%, 59.8% and 65.2% over the three days for linear patterns and 57.8%, 77.6% and

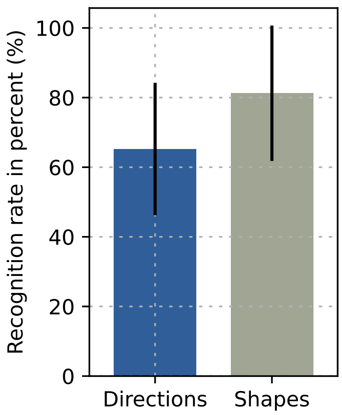

Fig. 5. Recognition rates averages by group of patterns, i.e. linear patterns referred to as directions and shapes.

81.2% for complex shapes. This can be explained partially by the fact that the velocities were chosen by each participants using a triangular pattern (classified as a complex shape). Therefore, the velocities chosen were more convenient for complex patterns and, as discussed with participants during the interview, too rapid for simple lines, therefore creating a bias towards more complex shapes. However, paired t-tests for each day showed that the difference between linear patterns and complex shapes is not significant ($t_1(7) = 0.1$, $t_2(7) = -2.23$, $t_3(7) = -1.72$, $p > 0.05$), see Fig. 5.

As for the impact of the direction of the stimuli, for the horizontal and diagonal lines, as well as for the circle shape, paired t-tests on day 3 showed there was no significant effect of direction ($t_{21}(7) = -1.02$, $t_{65}(7) = -1.37$, $t_{87}(7) = 0$ and $t_{1211}(7) = -0.24$, $p > 0.05$). The other patterns did not have a normal distribution, thus Wilcoxon matched pairs test were conducted. They also showed no significant impact of direction on the pattern recognition, $T = 6$, $T = 3$ and $T = 2.5$, $p > 0.05$ for the up/down, clockwise/counter-clockwise square and rotated squares respectively. There was also no significant difference between the rotated square and square patterns in counter-clockwise direction ($t(7) = -0.26$, $p > 0.05$) and in clockwise direction ($T = 3$, $p > 0.05$).

In terms of confusions, as illustrated by the confusion matrices (see Fig. 6), linear patterns and shape patterns were generally confused with other patterns from their respective groups. There were no tendencies in confusion between linear patterns, most likely due to the fast velocity issue. Concerning shapes, squares were most often confused with rotated squares, and respectively, in particular on day 3. Though there is no significant difference in the recognition rate, the rotation could be a source of confusion. This could also be partly explained by the participants' body positions, who sometimes shifted their body orientation to be more comfortable when putting their hands on the display. Circles in one direction were mostly confused with the circle in the other direction.

2) Questionnaire: At the end of the experiment, on the final day, participants were asked a few questions about their perception of the movement (continuity and fidelity to the shape) from their last experience and the impact of training, using 5-point Likert scales. Overall, the participants perceived the movements as relatively continuous, with a median rating of 3.5 on a Likert scale (1 = not at all; 5 = very much). Additionally, they felt that the training was highly effective, with a median rating of 4 on the same Likert scale.

They were further asked to rate the continuity (1 = discrete movement, 5 = smooth and continuous) and the fidelity (1 = not at all the same movement as the intended shape and 5 = identical to the intended shape) of each shape. The values for the medians are summarised in Tab. I. The tendency reflects the performance results, where linear patterns were in general more poorly rated than shapes, in particular for continuity, as they were deemed too fast to be properly felt. In addition, participants also reported the issue with the position of the hand on the prototype and the lack of contact of some parts, which affected the recognition. The rapid velocity exacerbated this difficulty. Indeed, participants mentioned that the part of the palm between the thumb and the index was not always in contact with the plate, and hence, patterns as the horizontal lines were harder to distinguish (pattern 2 on the confusion matrix). As for the shapes, only the circles were deemed not resembling the intended shape. We assume that the more trained they were, the more they could feel the motion flowing from one actuator to another and thus a square rather than a circle. In this case, creating a phantom position between the three closest actuators to improve the fidelity of the movement could be a solution, using Park et al.'s work [27].

Finally, they were asked to rate the perception of the categories of shapes, no matter the orientation or directions on a 5-point Likert scale with 1 = very difficult to perceive and 5 = very easy. Fig. 7 highlights again the same tendency: square, rotated square and vertical line were considered the easiest to identify, while horizontal line was rather mitigated and diagonal and circle considered the most challenging. The median scores were 2.5 for the circle, 3 for the diagonal, 3.5 for the horizontal, 4 for the square, 4 for the rotated square, and 4.5 for the vertical line, in increasing order.

IV. Discussion

The study demonstrated that dynamic shape patterns, based on apparent motion, could be conveyed to participants using the confinement of vibrotactile stimuli method. Contrary to previous work investigating the funnelling illusion with the same technology [28], participants did not feel separate actuators but felt a rather continuous movement, except for some patterns such as diagonals. Additionally, the participants reported that the perceived patterns closely matched their intended shape, except for diagonals and circles. This highlights the need for improvement in conveying these specific shapes, particularly circles. A solution could be to use the time modulation method instead with the improved algorithm of Park et al. [27] or to find a similar way with the amplitude modulation.

It is worth noting though that training played an important role, with an overall increase of 13.8% between the first

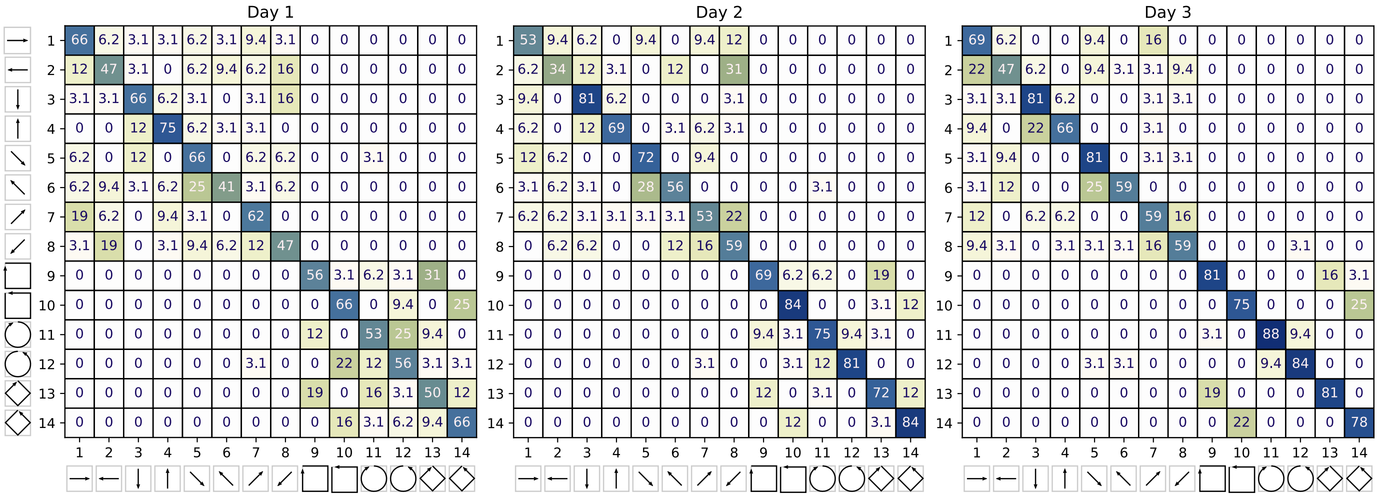

Fig. 6. Confusion matrices for each day depicting confusions between each pattern averages over all the participants (values in %).

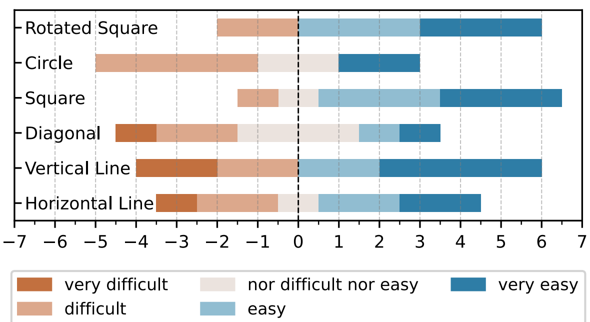

Fig. 7. Likert Scale repartition for the evaluation of perception for each type of shape. The blue colors indicate positive answers (i.e. ease of perception) while the orange answers indicate negative answers (i.e. difficulty of perception) and grey neutral answers. The numbers represent the proportion of answers.

TABLE I
MEDIAN VALUES FOR EACH PATTERN

		Continuity	Fidelity
1	Right	3.5	3.5
2	Left	2.5	3
3	Down	4	4
4	Up	4	4
5	Diagonal down right	3	3
6	Diagonal up left	3	3
7	Diagonal up right	2	2.5
8	Diagonal down left	2	2
9	Square clockwise	2	2
10	Square anti-clockwise	4	4
11	Circle clockwise	4	2
12	Circle anti-clockwise	4	2
13	Rotated square clockwise	4	4.5
14	Rotated Square anti-clockwise	4	4.5
	Linear patterns	**3**	**3**
	Shapes	**4**	**4**

and last day, improving from 58.3 to 72.1%. The recognition rates could be enhanced from the outset by enhancing the presentation of linear patterns, which received the lowest recognition scores. This was largely due to the participants' perception that the presentation speed was too fast, as reflected in their responses to the questionnaire. We initially hypothesised that these would be the simplest to recognise, however by using a unique speed, adapted from a complex shape, we created a negative bias towards the recognition of simple lines. In future work, other parameters adaptation depending on shape complexity could be investigated, e.g. depending on the number of edges involved or the overall distance.

Finally, we also varied directions (clockwise/counter-clockwise or inverted direction) for all patterns and orientation solely for the square (with a rotated version). The results showed no differences with these factors, with similar outcomes in both cases. For practical applications in real-world settings, it would be valuable to more extensively examine the impact of rotation (as by Sadia et al. [19]) and scale on shape recognition. However, this would require a larger number of actuators and could prove challenging given the gaps in contact implied between the palm of the hand and the surface.

V. Conclusion

This paper presented a preliminary study into conveying dynamic linear and complex shape patterns, using apparent motion, with the confinement of vibrotactile stimuli technique. The results demonstrated that using such a localised feedback technology was feasible. Participants could feel continuous movements and with training reached recognition rates overall of 72.1%. Participants felt complex shapes better, due to a too rapid velocity for linear patterns and issues with the lack of contact of some parts of the hand. Future work will investigate the fine-tuning of the velocity per type of pattern, as well as other strategies to improve the movement, in particular for circular shapes, and to take into account the hand contact. Such strategies include investigating the use of a sparse array, with touch sensing, as well as other rendering methods such as time modulation.

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