Recognition of 2D Shapes with Varying Complexity and Thickness on an Ultrasonic Tactile Display

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Abstract. Current haptic surfaces performing friction modulation still do not convey realistic shape sensations. In this study, we designed three elongated shapes that were rendered by ultrasonic lubrication within their inner area: a straight line, a sine and a second-degree polynomial. For these three shapes, we investigated how design properties such as the shape's complexity and thickness can influence users recognition of the displayed 2D shape and their strategy for haptic exploration on the display. A first experiment focused on recognition of shapes with varying complexity and on whether the increased or decreased friction within the shape impacts its perception. A second experiment focused on studying the influence of the shape thickness on the recognition rate of two shapes: the straight line and the sine. In experiment 1, participants recognized the line and sine quite well while performance with the polynomial was at chance level. In addition, whether friction was increased or decreased compared to the surrounding area did not impact shape recognition. In experiment 2, participants' recognition performance decreased for larger thickness. Analysis of the finger trajectory in experiment 1 showed that participants who followed closely the shapes performed better than participants who broadly scanned the surface. Taken together, our results suggest that friction recognition alone does not enable accurate recognition of straight or curved 2D shapes. However, parameters related to the friction contrast or the width of the stimulation area can enhance the user capacity to perceive shapes on the screen by touch.

Keywords: Shape recognition · Surface exploration · Friction modulation · Ultrasonic lubrication

1 Introduction

Devices that rely exclusively on touchscreens have become prevalent in our daily life, offering intuitive interactions alongside rich visual and auditory feedback

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[17]. However, despite their widespread use, these devices often lack haptic feedback. The absence of tactile feedback significantly hampers the interaction with the device, requiring a high level of visual attention throughout the user's actions [35].

To deal with this challenge, various types of tactile stimulation have been proposed to augment surface displays [3]. Vibrotactile technology is currently well-incorporated in touchscreens like mobile phones or tablets [13,16] but it has limitations for rendering specific cues such as force or friction. Another solution to improve haptic feedback consists of modulating the finger-surface friction on touchscreens. This approach aims to replicate the frictional and low-frequency properties of various materials and textures. Indeed, the finger is highly sensitive to friction modulation. It has been shown that touch is responsive to subtle frictional cues elicited by microscale properties of materials [10] and lateral force has been shown to convey geometry even when surface topography is incongruous [25]. Moreover, shear strains resulting from the compression of the skin have been shown to facilitate edge perception [12,24].

Currently, two main techniques are used for creating friction modulation: electroadhesion, which increases the finger-surface friction by generating an electrostatic attraction between the finger and the surface [14,20,27], and ultrasonic lubrication that reduces finger-surface friction by generating a thin layer of air, known as the squeeze-film effect, between the finger and the surface, in addition to intermittent contact induced by the vibration [28,31–33]. Ultimately, the change in friction induced by both techniques is perceived similarly by users [30]. Several studies using friction modulation have investigated path and shape perception. Agobert et al. showed that users can successfully follow a path relying solely on frictional cues [1]. Users can also associate friction modulations with primitive shapes when additional context is provided, such as three-dimensional relief in images [15], 3D shapes [21], or textures on the surface [4,34].

Studies have investigated the perception of important parameters of the simulated frictional cues such as a signal's intensity [11] and contrast [5,19], its waveform [29], the stimulus angle [8], and the influence of scanning speed [12]. However, very little research exists on the impact of tactile stimulation parameters on the user's ability to recognize 2D shapes rendered on the display. Sadia et al. [26] investigated 2D shapes with increasing number of angles in conjunction with three types of frictional patterns. They showed that shape recognition dropped and completion time rose when the number of edges increased above five. They associated the increased difficulty with a decrease of the angle sharpness. However, there are still many open questions about the capacity to perceive 2D-shapes through friction control, in particular regarding shapes with rounded corners that differ in parameters such as complexity, size, thickness, or frictional patterns.

In this study, two experiments were performed focusing on the shape's complexity and thickness. In the first one, three distinct shapes were generated with specific levels of intuitive complexity, ranging from a simple straight line to a more intricate second-degree polynomial. Two different contrasts between

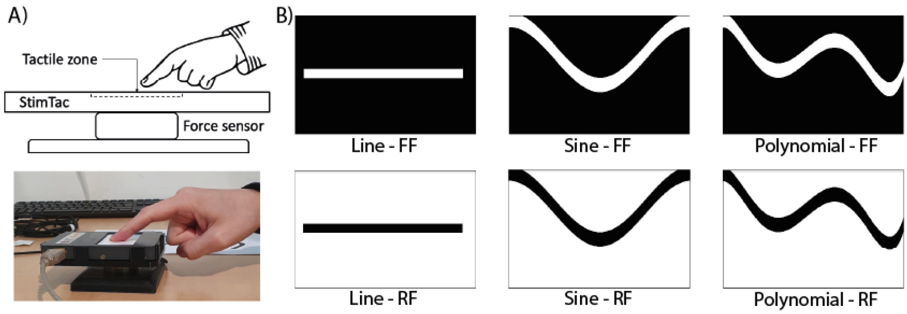

Fig. 1. Experimental set-up (A) The mounting of the StimTac ultrasonic device on a force sensor (B) Three types of elongated shapes (line, sine, and second order polynomial) are rendered with either falling friction (FF) or rising friction (RF) in the area of the shape.

the shape and its background were implemented: one with higher friction in the shape and another with lower friction in the shape. In the second experiment, we tested recognition of a straight line and a sine shape with three thicknesses ranging from 3 mm to 15 mm. The aim of the study was to find meaningful parameters for recognition of a two-dimensional shape on an ultrasonic haptic display.

2 Experimental Setup

The study is performed with the StimTac device [2], which generates waves at a resonant frequency of 34 KHz to create the squeeze film effect and intermittent contact [2] and controls the ultrasonic amplitude through localization of the finger's center of pressure. The stimulation area and amplitude are programmed using gray-scale images with a dimension of 512×256 pixels corresponding to 7.5×4.2 cm. Black pixels correspond to the absence of vibration and white pixels correspond to the maximal vibration amplitude that the device can generate, i.e. 2 µm peak-to-peak. In both experiments, a 6-axes force sensor was placed under the device, an ATI Mini 40 (ATI, USA) in the first experiment and a HEX 21 (Resense, Germany) in the second one (Fig. 1.A).

3 Experiment 1

Three 2D shapes with increasing complexity were designed for this experiment: a straight line, a sinus and a polynomial. Two methods of friction transition between the background and the shape's inner area were also implemented: Falling friction (FF) and Rising Friction (RF). For FF, lubrication is active inside the shape inducing a lower friction compared to the background. For RF, ultrasonic lubrication is active outside the shape inducing a higher friction (Fig. 1.B).

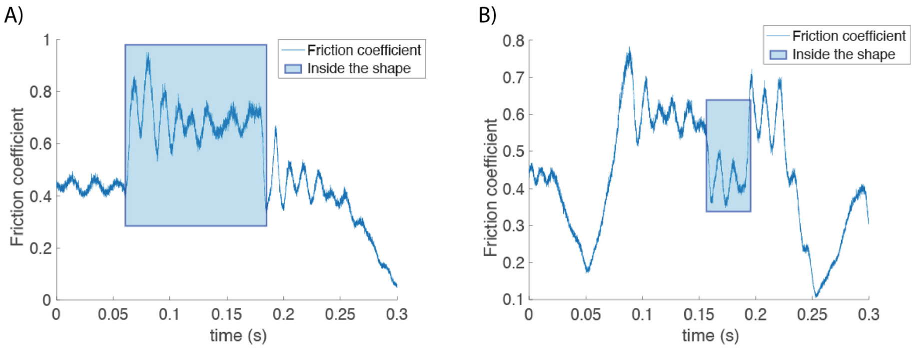

Fig. 2. The typical profile of the coefficient of dynamic friction's evolution is illustrated in A) when the finger passes through a shape with increased friction compared to the surrounding area and in B) when the finger enters a shape with reduced friction.

Following preliminary tests, the width of each shape was set at 4 mm. This size enables friction modulation to fully occur in both rising and falling friction cases. It also provides a relevant amount of area in which the finger can experience modified friction. The amplitude variation upon entering or exiting the shape has been maximized to 2 µm peak to peak to guarantee that frictional cues are well above the sensory threshold.

Control measurements of the dynamic coefficient of friction were conducted to verify if the friction variations were salient compared to the natural variations of the finger-surface friction. Passing through the form induced a rapid change of the dynamic friction coefficient, which was then kept respectively lower or larger while the finger was in the shape before returning to its natural dynamics (Fig. 2).

3.1 Experimental Procedure

18 healthy participants aged between 18 and 31 (mean = 21.7, SD = 2.7) performed a recognition task of the different 2D shapes. None of them had present or past injuries that could impact the result of our study. The study was conducted under active dynamic touch conditions, with participants using the index finger of their dominant hand to explore the surface of the StimTac. The study was approved by the ethical board of Sorbonne University under the protocol CER-2021-104. All participants gave written informed consent and the study was conducted in accordance with the Declaration of Helsinki. The experiment took place in a room with stabilized temperature and humidity.

Before the experiment, participants were given a piece of paper on which the different shapes were sketched to prevent giving accurate information about their precise location on the screen. This procedure was chosen as a trade-off because during the pilot experiments, participants had too much difficulty recognizing shapes with only an oral description. On the other hand, when they were provided with accurate visual representations of the tactile shapes, they used this

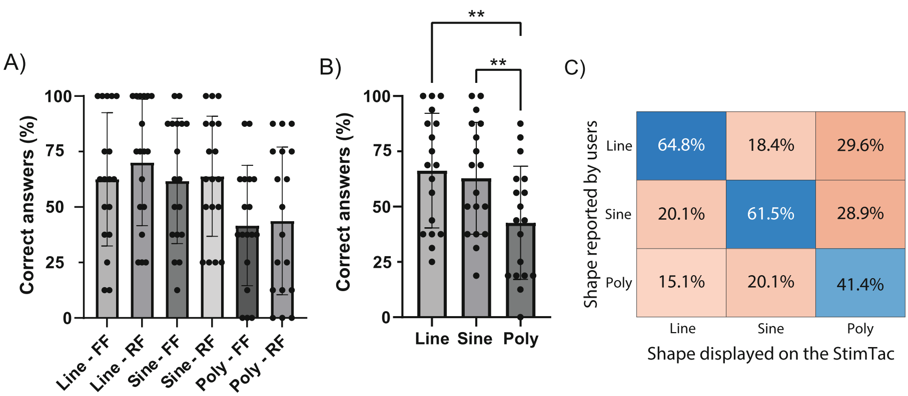

Fig. 3. A) Proportion of correct answers averaged across the individual performance for each of the conditions that were used during the experiment (Mean ± SD). The black dots represent the performance of individual participants for a given condition. B) Same plot as A in which the FF and RF conditions are merged.** corresponds to p < 0.01. C) Confusion matrix of the percentage of correct answers for each displayed shape type averaged across all participants as well as the average percentage of confusion with each other shape

extra information to choose where to probe the friction on the screen without actually exploring the shape.

Each combination of the three shapes and the falling or rising friction was repeated 8 times throughout the experiment for a total of 48 trials in pseudo-randomized order. In each trial, the participants had 30 s to explore the surface and to determine the shape displayed on the device. At the end of the 30 s or as soon as they are certain of their choice, they removed the finger from the display and reported which shape they think was displayed on the device.

3.2 Results

A first analysis on participants' ability to recognize 2D shapes was performed by computing the percentage of correct answers for each combination of a shape type and frictional condition (Fig. 3.A). The distribution of the answers for each condition satisfied the d'Agostino-Pearson normality test and the score for each condition was averaged across all participants. In order to study the effects of the frictional profile and shape type, a 2-way ANOVA statistical test was performed. The analysis showed a significant effect of the shape type (F (1.87, 31.71) = 10.43, $p < 0.001$) but not of the type of friction transition. Moreover, no interaction was observed between the friction transition and the shape type. Since the friction transition showed no impact, we organized the results per shape type (Fig. 3.B). The percentage of correct answers were 66.32 ± 25.92%, 62.85±25.32%, and 42.71±25.57% for the line, sine, and polynomial, respectively. A post-hoc Bonferroni-corrected t-test analysis with repeated measures between these conditions revealed a significant decrease in performance for the polynomial shape compared to both the line ($t = 4.14$, $df = 17$, $p = 0.001$) and the sine ($t = 4.19$, $df = 17$, $p = 0.001$). The statistical test did not reveal a significant difference between the line and the sine. Additionally, a t-test against the chance level (33,3%) was conducted. The results indicated that participants are able to differentiate the line and the sine above chance-level ($t = 5.40$, $df = 17$, $p < 0.001$ for the line, $t = 4.946$, $df = 17$, $p < 0.001$ for the sine) but not the polynomial condition. Thus, the results indicate that participants were unable to recognize the 2D polynomial shape on the tactile display.

Subsequently, our investigation focused on determining whether the difficulty in recognizing the shapes, especially the polynomial, could be attributed to specific similarities that might have led to confusion. For instance, participants may have experienced confusion due to the similarity in curvatures between the sine and the polynomial. To do this, we computed a confusion matrix showing the percentage of each possible answer when a given shape is displayed (Fig. 3.C). The confusion matrix shows that the polynomial is not specifically mistaken with the line or the sine. This suggests that participants' difficulty to recognize the polynomial shape is fundamental and their misclassifications were not due to a coincidental resemblance. Similarly, both the line and the sine did not present a distinct tendency towards a particular type of confusion.

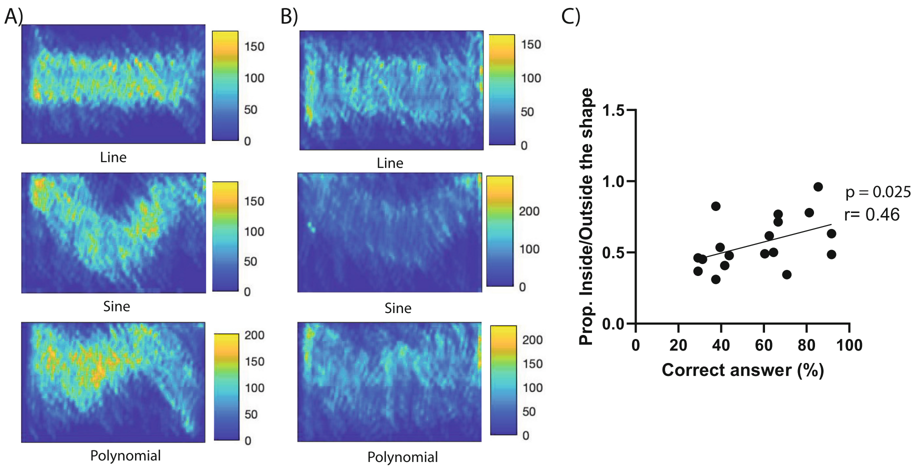

Fig. 4. Examples of a finger position heatmap that computes the number of times when the finger was located in each pixel throughout the entire duration of the experiment. Each heatmap represents the data for one shape and one user. A) depicts a user whose exploration strategy closely follows the shape, B) illustrates a user who scans the entire map, resulting in a scattered distribution of finger locations. C) Correlation between the percentage of correct answers and the ratio between the durations spent inside and outside the area.

By measuring the finger position and the three-dimensional contact force exerted by participants, we were able to analyze their exploration strategies through generation of heatmaps that compiled the finger positions from all trials featuring a specific shape. These maps depicted a wide variety of finger trajectories. Some users generated a distinct and clear representation of the shape on the heatmap, indicating that they closely followed the shape during the experiment (Fig. 4.A). In contrast, the finger positions appear more scattered for other users, suggesting that they explored the entire surface of the display to build their representation of the 2D shape made by modulated friction (Fig. 4.B). A Pearson correlation test revealed a significant correlation between the time spent inside the shape and the proportion of correct answers ($p = 0.0249$, $r = 0.47$) (Fig. 4.C). This correlation indicates that users who spend more exploration time in the area of the shape are more likely to accurately recognize its type.

4 Experiment 2

In this second experiment, we used two shapes from experiment 1: the straight line and the sine wave, since both of these were recognized above chance. In order to make the two shapes start at the same point, the horizontal line has been changed to a straight diagonal line. This change reduced the risk that participants would rely on trivial differences in the location of the two shapes, especially near the edges where comparison is easier.

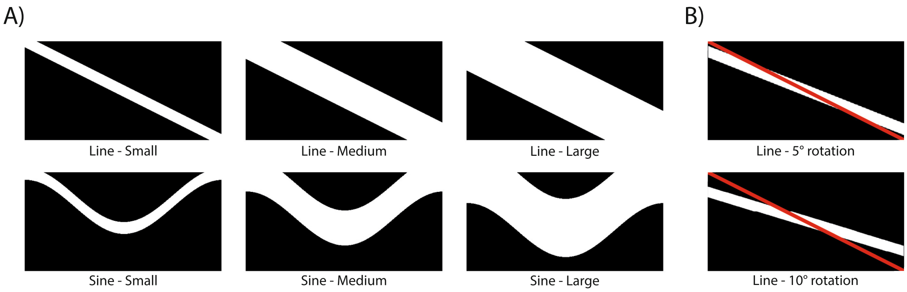

Fig. 5. A) The experiment involved six two-dimensional shapes, with two types of shape (straight line and sine) rendered in three different thicknesses: 3 mm, 9 mm, and 15 mm. B) 5° and 10° rotations of the "Line - Small" shape. The red line represents the original straight line without rotation

For each of these shapes, we selected three different thicknesses: 3 mm, 9 mm, and 15 mm. By choosing these three thicknesses we were able to cover a wide spectrum, allowing us to see whether these variations influence users' capacity to accurately identify the shape (Fig. 5.A). Additionally, each shape underwent a slight rotation with angles of 0°, 5°, and 10° to reduce the potential influence of learning effect and helpful points stemming from the shape's design. This

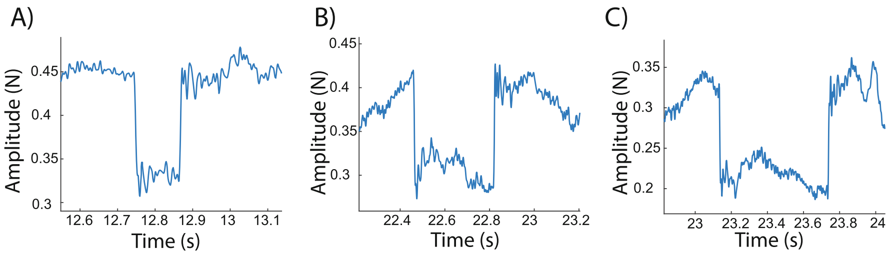

Fig. 6. The typical profile of the coefficient of dynamic friction's evolution is illustrated for A) 3 mm thickness, B) 9 mm thickness, and C) 15 mm thickness.

ensured that the shapes could be presented without participants being able to spot specific areas in which the two shapes are not overlapping and use this unwanted cue to perform the task (Fig. 5.B).

In this second part, the setup was identical to the first experiment. However, the sheet of paper given to the candidate before the experiment, containing the drawn shapes, was replaced by a graphical user interface on which participants selected one of the two possible shapes and one of the three possible thicknesses at the end of each trial. As in experiment 1, friction modulation was recorded throughout the experiment using the a force sensor placed under the device (Fig. 6).

4.1 Experimental Procedure

13 participants took part in this second recognition task. Like the previous experiment, participants were given 30 s to explore the surface using the index finger of their dominant hand. Following the exploration, participants were asked to first report the shape they thought they had explored and secondly its thickness using the graphical user interface. All combinations of the two shape types, the three possible thicknesses, and their rotations were pseudo-randomly repeated nine times, resulting in a total of 54 trials.

4.2 Results

The participants' capacity to identify a 2D shape was estimated by computing the percentage of correct answers for each type of shape (Fig. 7.A). The distribution of the answers for each condition passed the d'Agostino-Pearson normality test and the individual performances of participants were averaged. Observations reveal that more than 70% of the shapes were accurately identified, with $71 \pm 19\%$ (mean $\pm$ S.D.) for the straight line, and $72 \pm 17\%$ for the sine wave. These results surpass the chance-level and are aligned with the results from the first experiment.

To study how the thickness of a line affects the users' capacity to perceive shapes, the correct responses to each shape were split and categorized based on the three possible thicknesses (Fig. 7.B). Small and medium thicknesses were recognized above the chance level (50%) unlike the Sine-Large and Line-Large conditions. This shows the difficulty that participants encountered to recognize the shape in the case of large thicknesses. Data successfully passed the normality test of d'Agostino-Pearson and the average of the individual answers was computed. A one-way ANOVA was conducted for each type of shape. The analysis indicates a significant effect of thickness on the sine ($F(1.8, 21.7) = 6.449$, $p = 0.008$) and a more marginal effect on the line ($F(1.6, 18.9) = 3.79$, $p = 0.05$). In the case of the sine, a post-hoc Bonferroni-corrected t-test revealed a significant decrease in the user's capacity to perceive the large sine compared to the small sine ($t = 3.237$, $df = 12$, $p = 0.021$) and medium sine ($t = 2.793$, $df = 12$, $p = 0.049$). For the line, the post-hoc comparisons did not show significant results.

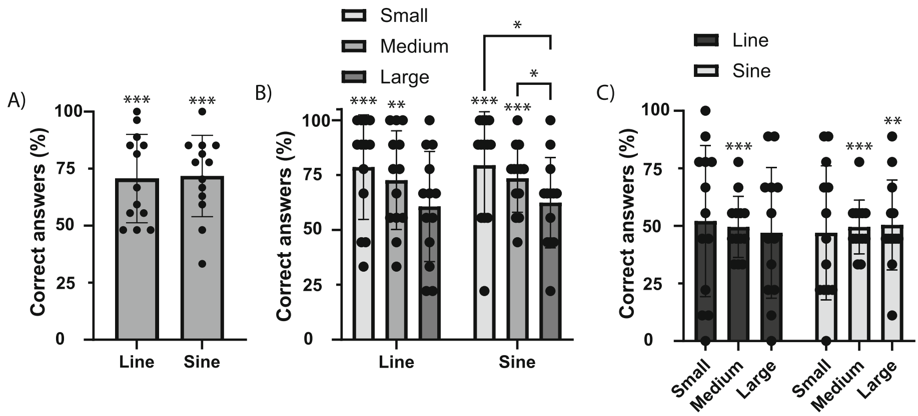

Fig. 7. A) The percentage of correct answers for recognizing the shapes, regardless of line thickness recognition, averaged across individuals (Mean ± SD). Each dot represents the performance of an individual participant. B) The same plot as in A, but the data were divided according to the shape's thickness. C) Percentage of correct answers in recognizing the thickness, regardless of shape recognition. Asterisks on individual boxplots correspond to the result of the t-test against chance level recognition. * corresponds to $p < 0.05$, ** to $p < 0.002$ and *** to $p < 0.001$.

We also explored whether the shape's thickness is recognized and whether performance depends on the type of shape. Similar to the previous test, the correct responses for each thickness were categorized according to shape and then averaged (Fig. 7.C). A t-test against the chance level was conducted, revealing that half of the variables do not significantly differ from chance level performance: $t = 2.069$, $df = 12$, $p = 0.061$ for Line - Small, $t = 1.741$, $df = 12$, $p = 0.107$ for Line - Large and $t = 1.699$, $df = 12$, $p = 0.115$ for Sine - Small. In addition, a one-way ANOVA was performed on each shape and showed that the type of thickness does not impact the participants' performance at recognizing how thick is the shape they are exploring. Thus, the inability of users to accurately discern thickness is widespread across conditions.

5 Discussion

This study evaluated users' ability to recognize a two-dimensional shape on a tactile display modulating friction. Performance was relatively low, even for the simplest shape, which was a straight line. Interestingly, recognition of sine waves did not differ from straight lines while second-degree polynomials already exhibited a complexity that prevented recognition above chance. The confusion matrix showed no dominant confusion between the specific shapes. Therefore, the observed performance levels likely stem from a more fundamental difficulty to form a mental representation of the shape during the haptic exploration.

No significant impact of the type of frictional modulation, increasing or decreasing, in the shape's area was observed even though humans perceive transitions with rising and falling friction differently [22]. It might be due to the largely over-threshold transitions used in our experiment and the fact that any shape of the experiment induced both types of transitions during exploration. Overall, these results are consistent with [26] and show that shapes with rounded corners might be even more difficult to distinguish since recognition among only three shapes already proved a hard task. In addition, our results reveal a significant impact of the shape's thickness on recognition, especially for the sine. Indeed, thicker shapes are harder to recognize and participants performed at chance level for the largest thickness. Interestingly, participants were generally not able to recognize the thickness of shapes, possibly because they could not precisely locate a given transition and sense whether they were entering or exiting the shape. Given that the primary question was about shape recognition, it is also possible that participants mainly focused on that task during the limited duration of a trial.

Finally, participants employed diverse forces and finger trajectories to explore the surface in experiment 1. Some of them maintained their finger close to the shape, while others scanned the surface more broadly. Users who adhered more closely to the shape were more likely to provide correct answers. However, the interpretation of this correlation bears limitations as a finger trajectory closer to the shape force might be a consequence of the user's better perception or its cause. Limitations of the haptic device also exist, as the requirement to exert a critical amount of pressure to receive haptic feedback could potentially have impacted haptic interaction hence the ability to accurately perceive the stimulus. Nevertheless, it is unlikely that this caused a major shift in performance.

6 Conclusion

This study showed that discrimination of 2D elongated shapes that are created solely by friction modulation is possible but challenging. Indeed, recognition becomes rapidly nearly impossible with a slight increase of the shape's complexity and thickness. This means that users did not feel the shape as a whole as they would have done with real shapes but had to create a mental representation from sparse cues. Thus, additional feedback seems necessary to convey a more realistic sensation of shape on tactile displays. A potential solution could be a richer frictional profile of the shape such as a texture within the shape. Since human are particularly sensible to small surface features [6] it might be beneficial to incorporate them to enhance the amount of information transmitted to the user's finger. However, such a solution can only be implemented when the shapes are wide enough to enable the finger to move across at least a few centimeters since ultrasonic modulation provides no cues to a motionless finger [11]. Thus, the creation of more realistic 2D shapes on tactile displays may necessitate complementary feedback to simple frictional cues such as vibrotactile cues [18], traveling waves that can create directional lateral force on the finger [9], or spatialization of the frictional feedback to allow for multi-finger exploration [7]. Furthermore, previous research has shown that vision and touch complement each other for correcting sensory errors induced by either sense during the perception of shapes [23]. Therefore, it is interesting to explore how complementary haptic and visual feedback can enhance each other on visuo-haptic displays.

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