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Exploring Low-Cost Grid-based Tactile Instruments for Understanding and Reproducing Shapes for People with Visual Impairments

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Abstract

While tools exist for blind people to understand shapes, these are not commercially available nor affordable and often require the assistance of sighted people. Thus, we designed two low-cost grid-based tactile tools using toggle buttons (TogGrid) and cotton balls (CottonGrid). To assess the potential of these as an educational tool, we conducted a user study with 12 people with visual impairments where they were asked to understand and reproduce shapes under different conditions. Although CottonGrid is relatively cheap and easy to make, findings show that TogGrid was perceived to be better in terms of perceived easiness, task completion time, accuracy, and preference in general. Particularly, participants valued TogGrid for enabling them to identify and correct errors. Based on the findings, we provide implications for utilizing toggle buttons for designing educational instruments for learning and expressing shapes for blind people.

Keywords: *Human-centered computing, Accessibility systems and tools, Empirical studies in accessibility, Shape understanding, shape reproduction, visual impairments, education tool, toggle button*

1. INTRODUCTION

Learning shapes or letters is important to people with visual impairments. When having a conversation, for instance, people often refer to specific letters to describe routes or appearances such as ‘U-turn’ and ‘L-shaped desk’ [1]. However, those who do not know what each shape looks like may feel frustrated when trying to process the key information. As Huckins [2] discussed, people with visual impairments also require understanding and drawing letters and shapes. Furthermore, writing names and signatures, which is an essential skill in daily lives on digital devices, has become common nowadays [3].

To enable people with visual impairments to learn shapes, various approaches have been explored. For example, LightWrite [1] focused on supporting independent handwriting learning for people with visual impairments at a low cost without additional hardware. They proposed a set of keystrokes to simplify the shapes of alphanumeric letters with audio feedback. However, it may not be efficient for understanding the shapes accurately without tactile feedback, which is known to be the most effective in understanding images and shapes [4,5] as it allows users to confirm their input immediately [6]. Although digital devices that provide

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instant tactile feedback to represent the drawn traces with dynamically raised lines exist [7], these are very expensive for individuals to purchase. ShapeCAD is another example that provides tactile feedback for understanding and modifying a 3D model for people with visual impairments when using Computer-Aided Design (CAD) [8]. However, it requires users to have some engineering skills to get access to the materials and assemble the pieces into a single model. To help people with visual impairments to understand and reproduce the shape more accurately and independently with direct tactile feedback with low cost, we designed two affordable grid-based tactile instruments; one uses cotton balls (CottonGrid) and the other uses toggle buttons (TogGrid) on a laser-cut wooden grid for learning and presenting shapes with tactile feedback (please refer to section 3 for details). To evaluate the two different designs, we conducted a user study with 12 people with visual impairments. The study consisted of two tasks: (1) shape understanding and (2) shape reproducing tasks. In addition, the tasks were conducted under two different representation modes (protrusion vs. depression) to assess the effect of representation on task performance.

As a result, we confirmed that understanding shapes in protrusions was easier than in depression for both designs. When comparing the two designs, participants commented that recognizing shapes with diagonals was easier with CottonGrid than TogGrid because the square-shaped buttons of two adjacent cells in TogGrid felt disconnected. Meanwhile, participants appreciate TogGrid because it was easy to count the number of cells and find the exact location as each cell was distinguishable from another by touch. Moreover, results showed that TogGrid outperformed CottonGrid for making shapes both in terms of accuracy and task completion time. The contributions of this paper are as follows:

- The proposal of TogGrid and CottonGrid, a low-cost accessible tactile instrument using a grid of toggle buttons and cotton balls.
- The empirical analysis of grid-based tactile approach for understanding and drawing tasks in terms of perceived easiness, accuracy, and task completion time.
- The suggestions for designing a future low-cost tactile shape learning instrument for people with visual impairments.

2. RELATED WORK

Our work starts from the idea to develop a low-cost instrument that is possibly be used in learning shapes and letters and drawing them on digital devices. We investigated several studies to develop our idea.

2.1 Learning Symbols and Letters

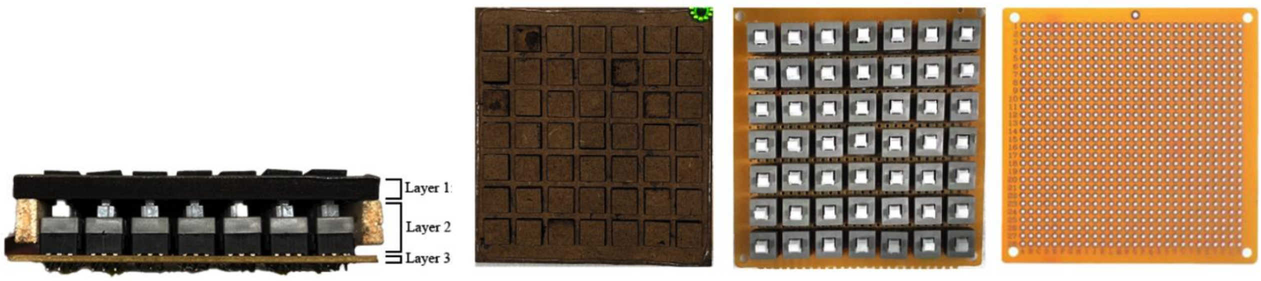
Several researchers focused on teaching symbols and letters to people with visual impairments over 50 years. In 1965, Huckins categorized the lowercase English alphabet to teach writing letters to people with visual impairments [2]. Before teaching letters, she taught students to memorize correct movements on paper with a pencil. Another method used two steps to teach letters [9]. The first step was to be familiar with moving hands and holding a pencil without delay. The second step was to help students to understand the shape of letters one by one. Gardner suggested another way to learn shapes by using embossed paper [10]. To create embossed paper, swell paper or embossed printer can be used. Swell paper (called capsule paper by the manufacturer) is coated with heat-sensitive chemicals and swells up when it is printed with black, and an embossed printer prints embossed shapes on the paper unlike common printers using ink or toner. Although those methods do not cost a lot, it is difficult to help draw or write shapes on the digital screen which cannot be swelled up or embossed. As digital devices become popular, instruments for learning handwriting or symbol are developed by using digital devices. Most of the research focused on using haptic or audio feedback to teach letters or shapes [11-15]. For instance, McSig published in 2008 [16] used a multi-modal system using a combination of haptic and audio feedback. McSig helped students with visual impairment to understand the movement of the teacher's pen and eventually to learn handwriting using the PHANTOM Omni force-feedback device. Another research used haptic feedback through a stylus pen [17]. The stylus pen connected to the computer transmits strong (active) or weak (passive) haptic feedback just like a teacher leading a student's hand, writing letters. However, even for the effectiveness of learning letters, devices used in previous studies are expensive for common people. For that reason, some researchers only used audio feedback to lower the cost of learning letters. LightWrite is the example [1]. They used audio feedback and simplified alphabets. The simplified alphabet is consisted of 7 shapes (short vertical line, long vertical line, 2 different diagonal lines, circle, right hook, and left hook), and the method starts by teaching those shapes first. After teaching shapes, they give audio instructions for writing letters to people with visual impairments using a combination of shapes. Melfi et al. developed a system called TPads. By including tactile paper and touchpad, TPads helps students with visual impairments explore tactile paper interactively with their two hands and audio description. The tactile paper that TPads can use does not limit to embossed paper but swell paper or thin 3d prints [18]. In addition, there was a study about implementing education instruments to understand the shapes of the sounds for students with visual impairments in high school. They had six versions of embossed tactile shapes that present various types of sound models to enhance their understanding of physics [19].

2.2 Drawing Symbols and Letters

There are a lot of studies focused on drawing symbols and letters using tactile instruments for people with visual impairments. Oh et al. [20] used pitch and stereo panning to follow the movement of writing letters. The most studied tactile instrument for drawing is the case of using a stylus pen. Watanabe and Kobayashi developed system for drawing symbols with stylus pen and pin-based tactile display. The pin-based tactile display is connected to computer and can be easily written stylus pen for people with visual impairments. With a stylus pen, people with visual impairments can identify the cursor point and feel the vibration of tactile display while drawing lines [21]. In another research, there was a study on implementing drawing instruments that allow users with visual impairments to create images with two-dimensional tactile pin matrix displays. While writing with a freehand stylus, the display provides real-time feedback on lines drawn so that people with visual impairments can recognize the shape they draw [22]. While they focused on stylus pens to recognize shapes for people with visual impairments, some research paid attention to the use of a mouse cursor to draw lines. They implemented grid-based drawing instruments with auditory feedback to navigate the drawings [23]. Headly et al. developed a tactile instrument with different amplitude in haptic display for people with visual impairments to discriminate patterns through touch [24]. Similarly, Kamel et al. developed an instrument that gives direct tactile feedback when people with visual impairments drew symbols on it. They have designed and experimented with the idea that lines can be concave into thin plastic so that your actual drawing can be felt by touch [25]. There is another study that focused on the tactile instrument to create 3D objects [8]. Their idea starts by giving access to people with visual impairments to design 3D in computer-aided design (CAD). They designed the tactile instrument to represent and modify 3D models with CAD.

3. GRID-BASED TACTILE INSTRUMENTS FOR SHAPE LEARNING

We propose two instruments for understanding and reproducing shapes for people with visual impairments: TogGrid and CottonGrid. As shown in Figure 1, TogGrid has three layers: (1) a laser-cut wooden panel, (2) a grid of toggle buttons, and (3) a phenol-printed circuit board (PCB). Note that the size was chosen to fit into a palm to be portable. More details are below.



(a) *TogGrid* - Side view (b) Layer1: *Wooden Grid* (c) Layer2: Toggle buttons (d) Layer3: A phenol PCB

Figure 1. The overview of *TogGrid*

• Layer 1: A wooden panel. It is the top layer, and its purpose is to show the grid and enable users to press each toggle button at ease by providing a relatively large and even surface since the contact area of the toggle button is too small. As shown in Figure 1b, a small, squared button cover that users can press is $8mm \times 8mm$ and the thickness of the panel is $4.5mm$. The wooden panel was laser-cut to be placed on top of a grid of toggle buttons. The size of the grid is $8cm \times 7.4cm$.

• Layer 2: Toggle buttons. It is the main layer with a 7×7 grid of toggle buttons [1] as shown in Figure 1c. The size of the button is $5.8mm \times 5.8mm$, and the space between the two buttons is $1mm$. As a toggle button, it can have two states: lowered when the button is pressed down and raised when the button is pressed again.

• Layer 3: A phenol PCB. To be able to transfer the toggle states to a digital device (e.g., PC, smartphone), we also include a bottom layer, which is a 28×28 phenol PCB (Figure 1d). Each toggle button is soldered to this board and connected to an Arduino Mega.

To build the prototype, we first soldered toggle buttons on the PCB board, and then connect each toggle button with Arduino input pin. The last step was to put on wooden grid on the top of the button grids as a cover. We also developed custom software using Arduino IDE and C++. It detects the changes in the state of a toggle button as 0s and 1s for depressed and pressed, respectively [2]. As for CottonGrid, we used the same wooden grid (Layer1 for TogGrid) but used cotton balls to represent shapes by either filling in or emptying out each cell in a grid. The total cost of building TogGrid was about $10.0 for TogGrid: laser cutting costed $5.0, 49 toggle buttons (about $0.1 each), and the wooden panel costs $0.35[3] On the other hand, the cost is cheaper with CottonGrid; it was approximately $6.0 in total: laser cutting ($5.0), cotton balls (about $0.8 for a bag of 50 cotton balls), and the wooden panel ($0.35).

4. METHOD

To assess the effectiveness of our proposed instruments, we conducted a user study with 12 participants with visual impairments. It was a single-session study consisting of the following tasks:

• Task1. Shape Recognition: Recognizing shapes by touch
• Task2. Shape Reproduction: Reproducing the recognized shape presented in Task1

4.1 Participants

We recruited 12 participants via word-of-mouth from local organizations for people with visual impairments. Their age was 40.4 on average (SD = 11.1) and all of them were male. Nine of them were totally blind (4 of them were congenital), two could barely recognize the shape of objects in front of their eyes (P5 & P8), and one (P12) had low vision. All but P8, who was learning to read and write Braille at that time, were proficient in Braille. Please refer to Table 1 for details.

Table 1. Participants' demographic information

ID	Age	Blindness	Onset	Braille Proficiency
P1	29	Totally blind	5-10 years	Expert
P2	50	Totally blind	>10 years	Expert
P3	34	Totally blind	Since birth	Expert
P4	40	Totally blind	>10 years	Expert
P5	64	Shape recognition	3-5 years	Expert
P6	28	Totally blind	Since birth	Expert
P7	27	Totally blind	Since birth	Expert
P8	38	Shape recognition	3-5 years	Novice
P9	39	Totally blind	Since birth	Expert
P10	51	Totally blind	>10 years	Expert
P11	36	Totally blind	5-10 years	Expert
P12	49	Low vision	5-10 years	Expert

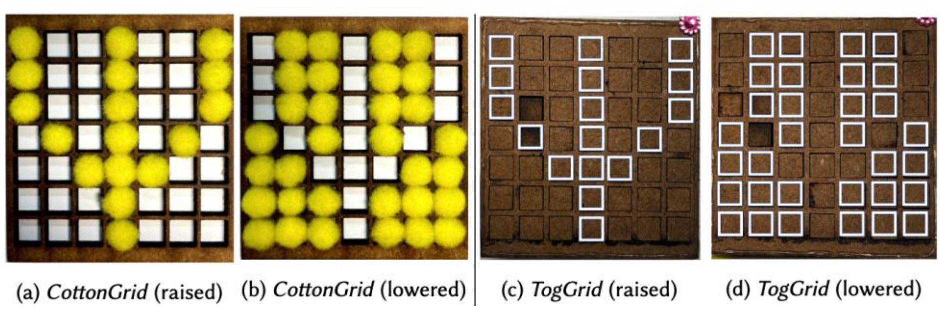


Figure 2. Examples of (a) raised and (b) lowered *CottonGrids*, and (c) raised and (d) lowered *TogGrids*. The represented shape is a Greek letter Ψ (psi) as in Figure 4b. As for *TogGrid*, cells with white borderlines indicate the ones that are raised.

4.2 Conditions

To assess the effectiveness of the two grid-based instruments, we examined the effect of Instrument (2-level: CottonGrid vs. TogGrid). We also investigated Representation (2-level: protrusion/raised vs. depression/ lowered) to check if prior findings that protrusions are better than depressions for tactile representation of shapes and letters ([26,27]) can be generalized to the proposed instruments. Please see Figure 2 for examples.

4.3 Apparatus

As shown in Figure 3, participants were seated in front of a desk with a mat laid on the desk during the study. For the instruments, we placed a tactile sticker at the top right corner of each grid as a reference point for all conditions and cotton balls were placed on top of a desk for Task2 (shape reproduction task). The angle of the camera was set on the mat so that camera can record the participant's hands, work progress, and results. Additionally, we set up a voice recorder to record participants' responses throughout the tasks. The performance time for each task was measured by asking participants to directly press the remote controller immediately before and after the task. After the completion of Task2, we took a picture of the shape made by each participant to assess the accuracy.

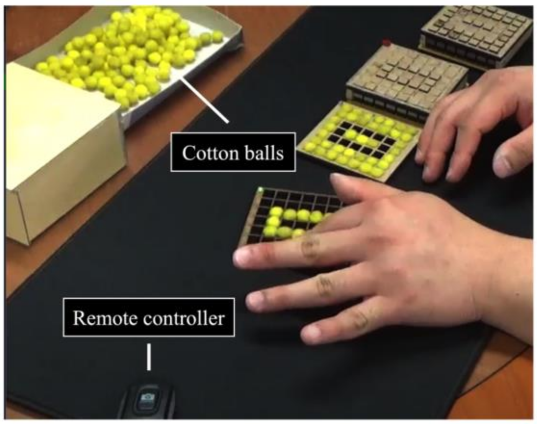


Figure 3. The demonstration of the experiment setting during the tutorial in Task1. Participants were asked to touch four different conditions representing the same shape.

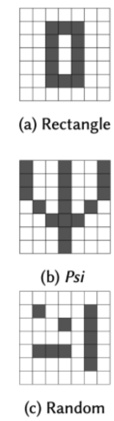


Figure 4. Shapes used for the tutorial (a), and the actual tasks (b, c) on a grid.

4.4 Procedure

The session began by signing the consent from after the content was read out to the participants. Then, there was a brief interview that consisted of seven questions, asking demographic information such as participants' age, gender, and visual impairment as well as their experience with learning Braille, letters, and shapes. After then, the participants were asked to perform two tasks. As for Task1 (shape recognition task), we asked participants to learn the same shape by touch under four different conditions at a time as shown in Figure 3. Participants were then asked to rank the four conditions of the instruments in the order of perceived easiness. As for Task2 (shape reproduction task), participants were instructed to use each of the four instruments to reproduce the shape that they had just learned in Task1. The instruments were presented one at a time. For making the raised ones, participants were given an empty grid for CottonGrid, and all toggle buttons were pressed down for TogGrid to begin with; vice versa for the lowered ones. After completing the task with all four conditions, we asked to rank the instruments that were easiest to reproduce the shape. Prior to each task, a tutorial was given with a simple rectangle shape (Figure 4a).

This was repeated twice; one with an alphanumeric letter (Figure 4b) and a random shape (Figure 4c) in a counterbalanced order. Note that these two shapes were chosen as these vary in size, connectivity, and symmetry. Also, these characters consist of multiple elements such as dots, curves, straight horizontal and vertical lines with different locations and lengths.

After completing all two tasks for one shape, the procedure was repeated once more for the other shape. Half of the participants performed psi first and the other half performed random shape first. In the end, the experimental process is completed with questionnaires about the difficulty of the two shapes.

4.5 Data Analysis

For the analysis, we collected subjective ranking data for perceived easiness and accuracy for understanding and reproducing shapes as well as preference, which was converted the ranking into a score (i.e., 3 points for rank1, 2 points for rank2, 1 point for rank3, and 0 point for rank4). We also assessed the accuracy of reproduced shapes in Task2 in terms of correct rate (%) by counting the number of missing and miss-positioned cells out of the total number of cells that need to be presented to make the target shape (i.e., 17 for psi and 10 for random shape). To be specific, for psi, we deducted 0.3 points for every offset (e.g., 0.3 if the cell is located at one of the 8 neighboring cells of the target cell within a grid and 0.6 for the next layer of 16 neighboring cells) and 1 point per missed or extra cell from 17 and multiplied 100 to compute the accuracy. We also measured task completion time. For quantitative data, we conducted one-, or two-way ANOVA and post hoc pairwise comparisons with Holm's Sequential Bonferroni adjustments if applicable to protect against Type I error. We only report the ones that were found to be significant.

As for the qualitative data, we assessed the interview responses before performing tasks and the subjective feedback during and after completing tasks. These data were coded into themes by two of the researchers as in [28].

5. FINDINGS

5.1 Prior Experience with Braille, Letters and Shapes

When participants were asked about their prior experience, all twelve participants responded that they have learned to read and write Braille. The method of learning Braille varied by participants. However, all learned Braille with tactile feedback except for P11 who learned Braille with printed materials before losing his vision. To be specific, some had access to a stylus and papers for Braille writing ($N = 2$) or a tactile educational tool made of steel for Braille learning ($N = 1$). Others had more casual ways of learning Braille. For instance, one participant learned Braille without a tool but used index and middle fingers where each of the three phalanges (i.e., the distal, middle, and proximal) of the palm side is considered as a place for each cell of six braille dots.

All of the participants also have learned to read and write letters including all four participants who were congenitally blind, who have learned letters with tactile feedback by touching alphabets on a piece of paper written with a glue gun ($N = 3$) or letter-shaped magnets ($N = 1$), similar to how they have learned Braille. The remaining eight participants learned letters before losing their vision later in their lives.

Regarding shapes, three out of four participants who were blind since birth responded that they have learned shapes at elementary school with tactile feedback including a textbook and a stencil ruler for shape drawing. In addition, we asked if they have drawn any kind of letters or shapes on a touchscreen after losing their vision, the half of the participants (P1, P2, P6, P7, P9, and P11) answered 'yes'. They have drawn shapes on a touchscreen to unlock their smartphones using a pattern ($N = 5$) and P6 said he had signed an electronic document at a bank.

5.2 Perceived Easiness for Understanding and Reproducing Shapes

After completing Task1, we asked participants to rank the four instrument conditions in terms of perceived easiness of understanding shapes. As shown in Figure 5a, we found that participants perceived the raised on regardless of the type of the instrument across the shapes; $F(1) = 31.63$, $p < .001$ for psi and $F(1) = 32.36$, $p < .001$ for random shape. In addition, we also found that TogGrid was perceived to be easier than CottonGrid when trying to understand random shape regardless of the representation types; $F(1) = 12.64$, $p = .001$. Moreover, results showed that the instrument that was perceived to be the easiest differs depending on the shapes (i.e., CottonGrid for psi, and TogGrid for random shape). Note that none of the participants knew psi letter.

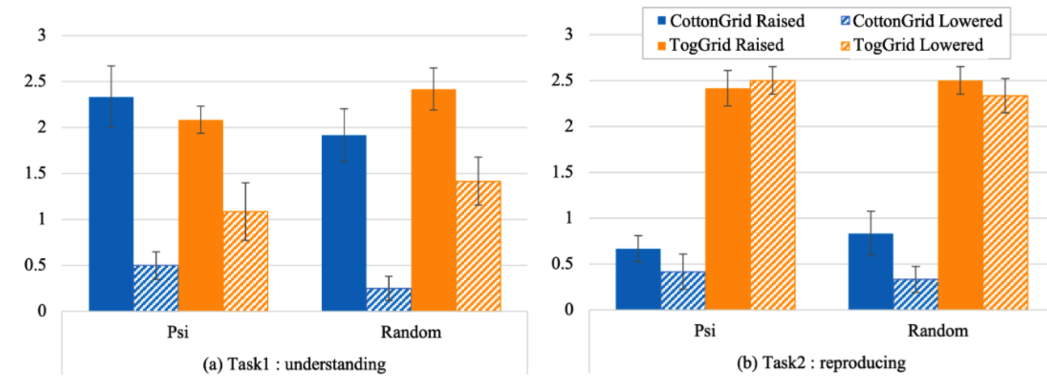


Figure 5. The average perceived easiness scores for (a) understanding shapes in Task1, (b) reproducing shapes in Task2 (0-3; 3 is best for all). Error bars indicate standard errors (N=12)

While there was a strong preference for raised version regardless of instrument type when understanding shapes, the representation mode did not matter much for reproducing shapes. To be specific, when asked to rank the instruments in terms of perceived easiness of reproducing shapes (Task2), most participants perceived either raised or lowered version of TogGrid as the easiest for both shapes; see Figure 5b. Two-way ANOVA with factors of Representation and Instrument revealed that the difference is significant for both shapes; the main effects of Instrument were $F(1) = 125.13$, $p < .001$ for psi, and $F(1) = 98.58$, $p < .001$ for random shape.

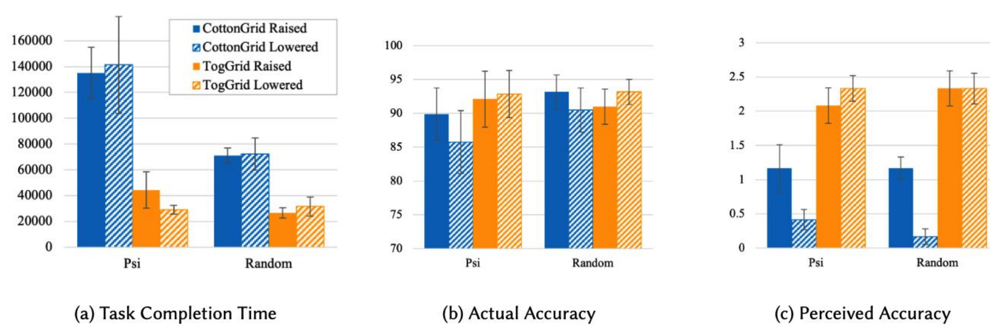


Figure 6. (a) The average task completion time in miliseconds in Task2, (b) the actual accuracy in terms of correct rate (%), and (c) the perceived accuracy (1-3; 3 is best) on average for Task2. Error bars indicate standard errors (N = 12).

5.3 Task Completion Time for Reproducing Shapes

In addition to subjective ratings, we measured participants' task completion time for reproducing shapes for Task2 and the average is shown in Figure 6a. Two-way ANOVA with factors of Instrument (2-level: CottonGrid vs. and TogGrid) Representation (2-level: Raised vs. Lowered) revealed that there is a main effect of Instrument for both shapes ($F(1) = 20.44$ for psi, $F(1) = 27.59$ for random; $p < .001$ for both) suggesting that participants were faster at reproducing shapes with TogGrid than with CottonGrid across different shapes and representation type.

5.4 The Actual and Perceived Accuracies for Reproducing Shapes

We also assessed the accuracy of reproducing each shape using each of the conditions in terms of correct rate (%). As shown in Figure 6b, the actual accuracy was almost the same across instruments and shapes in

Task2 without any significant interaction or main effect for Instrument and Shape. However, the accuracy perceived by participants after reproducing shapes in Task2 was significantly higher for TogGrid than that for CottonGrid regardless of the representation mode for both shapes; see Figure 6c. For psi, we found a significant interaction effect ($F(1,3) = 4.1$, $p = .049$). While the average score was not statistically different between raised versions of the two instruments, the perceived accuracy was significantly higher for TogGrid than CottonGrid between lowered versions ($t = 9.93$, $p < .001$). On the other hand, for random shape, for which we found a significant interaction effect ($F(1,3) = 6.39$, $p = .015$), TogGrid was perceived to be more accurate than CottonGrid for both raised ($p = .015$) and lowered ones ($p < .001$).

5.5 Subjective Feedback

5.5.1 Shape Understanding. Participants commented that CottonGrid and TogGrid are different in terms of expressiveness when understanding shapes. To be specific, participants thought that TogGrid is limited when trying to express the connectivity of adjacent cells, particularly the ones with curves or diagonals ($N = 7$).

> *"That one [TogGrid] does not feel like the [diagonal] lines are connected. But this one [CottonGrid] curves very smoothly. (P2)"*

On the other hand, participants felt that TogGrid was more evident when representing precise information such as the exact location of a dot (i.e., a single cell with no neighboring cells) and the length of a straight line ($N = 5$) either ($N = 5$). Four of them specified that TogGrid is easy to count the number of cells, unlike CottonGrid which is difficult to tell one cotton ball from another when they are next to each other ($N = 4$). One of them felt that it is more obvious to understand the shape because the size of the toggle button is bigger than that of the cotton balls for CottonGrid.

Concerning the effect of representation type, we asked participants to rank the four conditions in Task2 in terms of perceived easiness of understanding shapes, 10 out of 12 participants reported that raised versions were easier than the lower ones mainly because they are already familiar with them from their prior experience with Braille with raised dots. Participants specified that,

> *"I think I'm more used to touching raised ones because the tool for learning Braille is like that." (P3)*
> *"Lowered versions are difficult. I think it's confusing because I tend to recognize raised ones as shapes [not the lowered ones]. I am better at recognizing raised ones." (P10)*

5.5.2 Shape Manipulation. Eight participants specified that it is simpler to manipulate the state of each cell (i.e., raised or lowered) with TogGrid compared to CottonGrid because it is easy to find the precise location ($N = 7$) and robust as the buttons are at a fixed location within a grid. Related, participants also commented that it is fast to reproduce shapes ($N = 4$), and it allows them to use both hands ($N = 4$). They said,

> *"It [TogGrid] is fixed, so I could do it faster by pressing it with both hands at the same time." (P8)*
> *"The toggle button [TogGrid] was easy to repeat and modify because it can be pressed and unpressed from the fixed part." (P9)*

On the contrary, participants complained that cotton balls for CottonGrid get easily lumped together, which makes it hard to take only one ball ($N = 4$), and that balls get easily popped out from the grid ($N = 9$). P11 stated,

> *"Since it [TogGrid] has a fixed frame, I just need to press the position I want. But with the grid [CottonGrid], I might spill the cotton balls while taking them out from the frame. I have to find where the cotton balls go. It's hard."*

When two representation types were compared, participants' feedback was similar for TogGrid between the raised and the lowered version. However, the feedback varied for CottonGrid. Most of the participants mentioned that it was complicated to reproduce shapes with raised version because there are many procedures such as picking up cotton balls, finding the cells, and putting the balls in (N =9). On the other hand, in the case of the lowered version, participants thought that reproducing shapes is relatively simple as all they need to do is find the cotton ball at the target cell locations and pop it out from the grid although there is a risk of taking the wrong one out or other losing non-target balls as these get fall out during the manipulation (N = 5).

5.5.3 Shape Review and Correction. All participants appreciated TogGrid as it enables participants to review the shape during or after entering shapes. In particular, three of them liked that they were able to correct any mistake they made after finding errors. Participants said,

> *"It [TogGrid] was intuitive because it was more convenient to make changes. I could immediately understand the current shape right away and know my progress on the go while making the shape." (P1)*
>
> *"It [TogGrid] was convenient to repeat and make modifications because it can be easily pressed and unpressed from the fixed part. It's like writing on a computer [TogGrid] versus writing on a piece of paper [Baseline and Grid Overlay]." (P9)*
>
> *"The location information is not precise, and I could not know where the shapes meet with each other. Also, I couldn't tell for sure how the shape is drawn." (P10)*

5.5.4 Form Factor. Participants also commented on form factors. They liked the cotton ball from CottonGrid for its soft texture (N = 4), round shape (N = 4), and small and consistent size (N = 1 for each). Meanwhile, one did not like its small size as it makes it hard to count the number of balls, and another participant did not favor the cotton ball because its shape is deformable; the shape changes when pressed, unlike the toggle buttons with a hard surface. As for TogGrid, participants did not like the squared button shape (N = 6), which is related to expressiveness. P7 specified,

> *"As TogGrid's cover is square, I think it's hard to express diagonal lines."*

In addition, participants wished TogGrid to have a greater height difference between the two states of the button (i.e., raised vs. lowered), consistent height when the buttons are raised, and wider space between buttons (N = 1 for each). In the case of Grid Overlay, participants complained that the grid was movable as it was fixed with a rubber band instead of a permanent installation (N = 3), and the thickness was too thin or too thick (N = 1 for each).

6. DISCUSSION

6.1 The Potential of TogGrid as an Instrument for Learning Shapes for People with Visual Impairments

From the interview, we confirmed that various tactile instruments are widely used by blind students to learn educational material through a sense of touch as found in [29], which is known to be effective [30]. In addition, all of the participants who are congenitally blind have learned letters and shapes reflecting prior findings that blind people need to learn the visual appearance in addition to Braille characters as in [2]. Moreover, we found that drawing a shape or writing letters on a smartphone is quite common. Our findings show that TogGrid meets these needs as an educational tool for learning and reproducing shapes and letters in terms of perceived easiness, efficiency, accuracy, and preference.

Yet, further study is needed to investigate how TogGrid can be used to teach and learn various kinds of graphical figures such as graphs and maps at schools as an educational instrument.

6.2 Supporting Shape Understanding with Easily Distinguishable Cells for Grid-Type Representations

As described in subsubsection 5.5.1, most of the participants preferred protrusion for understanding shapes, where raised cells are used to represent the target shape regardless of instrument type and shape as found in previous studies [26,27]. Although there was no statistical difference between the two instruments for the shapes we compared in terms of perceived easiness, participants expressed their preference for CottonGrid for psi and TogGrid for random shape. This is because CottonGrid it is not good for representing the connectivity of curves and slope lines (i.e., non-vertical or non-horizontal), which is included in psi only. On the other hand, they perceived that TogGrid is better for random shape since identifying the precise location of a target cell and the length of a straight line (i.e., T-shape or L-shape) is easier with cells being more distinguishable from another. Since most of the shapes include both straight lines and non-straight lines, the shapes that TogGrid can support are not limited. Inspired by the round-shaped cotton balls from CottonGrid, changing the shape of the cover of toggle buttons in TogGrid from square to circle may resolve this issue. Since the first layer of TogGrid is easily detectable, we suggest preparing both round-, and square-shaped button covers and mix-use them to best represent target the shape. Moreover, it is highly recommended designers have non-deformable covers with uniform height, and sufficient height difference between the pressed-, and the released buttons so that users can easily identify the state of the toggle button (i.e., raised or lowered).

6.3 Supporting Efficient and Accurate Shape Reproduction

Unlike the perceived easiness for understanding shapes, the effect of Representation on perceived easiness was not observed for reproducing shapes in Task2; TogGrid was perceived to be easy and fast compared to CottonGrid for both raised and lowered versions. One explanation is that the process of reproducing shapes is much simpler for TogGrid (i.e., find the location and press the button) than CottonGrid, which requires participants to find the exact location, reach out for the cotton balls and grab one, and place the ball at the target location in the case of the raised version. While the process is simpler for lowered version as all they need to do is take the balls out from the grid, they were concerned that wrong balls may come out and it would be difficult to place them back in if they cannot find the missing ball. Interestingly, while participants were slower at making psi than random shape which is expected as psi requires more number manipulations, the difference between shapes seems neglectable for TogGrid, unlike other conditions. We believe this is due to the ease of using both hands with TogGrid, which is helpful when reproducing a symmetrical shape. Since random shape is not symmetrical, we expected that participants will have the feeling of difficulty reproducing random because arbitrary shape must be hard to memorize. However, the result showed that participants did not feel random was inferior in difficulty. Participants also appreciated TogGrid which is accurate at finding the exact location by counting cells on the way which is easily identifiable from one to another and that it enables them to check the current status and find or correct mistakes if any. We expect TogGrid to support blind people to learn shapes and letters independently with high confidence.

6.4 Limitations and Future Work

As a single-session study, our study has some limitations. First of all, while we were able to assess the performance of the proposed system in terms of various metrics (e.g., perceived easiness, accuracy, and task completion time), needs further investigation to confirm if the participants have learned the shape and if they can remember it after a certain period. Moreover, although we were able to run some statistical tests and revealed significant results with small sample size, a greater number of shapes and participants would be needed to be able to generalize the results. In addition, since we cannot address how our proposed instrument can be used in the actual educational settings for teachers and students as a controlled lab study, a long-term field study would be needed. Lastly, we did not explore how the proposed tool can be used to support more complicated letters such as Chinese characters, which would require higher resolution than 7 × 7 as in our system. In future work, we plan to improve the expressiveness of TogGrid by adding buttons with multi-level states, and different button covers with varying shapes and textures, supporting higher resolutions (e.g., 12 × 12 grid) to convey more complex visual figures more accurately while reducing the costs.

7. CONCLUSION

We proposed two low-cost grid-based tactile instruments to support blind people in learning shapes. To assess its effectiveness, we conducted a user study with 12 people with visual impairments where they were asked to understand and reproduce two different shapes (psi vs. random shape) under different conditions varying the type of instrument (CottonGrid vs. TogGrid) and representation modes (raised vs. lowered). Findings show that TogGrid outperform CottonGrid in various metrics. Most of all, it was perceived to be easy, especially when reproducing shapes as it not only allows users to check the current status but also identify errors and make revisions on the go. However, CottonGrid was perceived to have a better form factor enabling users to express diagonal or curved lines. Based on the lessons learned, we plan to improve our system focusing on improving expressiveness and investigate how it can help learning new shapes in educational settings.

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