3D-Printed Models for Optimizing Tactile Braille & Shape Display

Maryam Etezad, Rajeev Joshi, Robert Alexander, and Franceli L. Cibrian

***Abstract*—Existing market-available refreshable Braille displays (RBDs) offer limited functionality at a high cost, hindering accessibility for individuals with blindness and visual impairment for teaching and learning purposes. This motivates us to develop a multi-functional, compact, and affordable RBD tailored for educational institutes to enhance teaching and learning experiences. We propose the development of BLISS (Braille Letters and Interactive Shape Screen), a novel RBD, that BLISS presents a unique configuration arrangement of Braille cells that accommodates up to six letters at a time and shapes by reusing the Braille pins. To determine the optimal specifications, including size, Braille cell spacing, and pin configuration, we fabricated and evaluated 3D-printed sets, mimicking how BLISS would display letters and shapes. We tested 36 variants of 3D-printed sets with 8 individuals with blindness and visual impairment and found that conventional Braille spacing is insufficient for accurately representing shapes. Hence, BLISS will introduce a novel design that uses a pin configuration to raise the extra pins to present shapes and lower them for Braille letters, providing dual-mode operation. Our findings show the potential of BLISS to display both Braille letters and shapes on the same refreshable display, offering a novel, compact, and cost-effective solution.**

***Index Terms*—Refreshable Braille display, shape display, Braille reading, early literacy Braille device, haptic rendering, Braille cells, tactile graphics, piezoelectric benders.**

I. Introduction

ACCORDING to the National Braille Press, only one out of five children with blindness and visual impairments[1] engage with Braille, while a staggering 84% attend public schools, where Braille instruction may be as minimal as one hour per week [1]. Compounding this issue is that qualified Braille teachers are scarce, further impeding access to this crucial skill [1]. The significance of Braille cannot be overstated; it is an indispensable tool in fostering literacy for individuals with blindness and visual impairments. Millar investigated the learning process of a tactile reading system and its relationship to the represented language in [2]. Braille retains its relevance even in the digital epoch, serving as a bridge to information accessibility. The basic Braille system uses a combination of six raised dots inside a Braille cell (3×2 or 4×2), giving a combination of 64 signs. Each sign represents a one-to-one mapping of letters, numbers, and special characters that are embossed on paper, creating a traditional writing page text consisting of 25 lines and 43 characters of textual information [3]. In addition to learning Braille letters, shapes are needed to represent various objects, such as maps, graphs, and diagrams, which can be challenging to understand through text alone [4], [5]. Even simple shapes such as musical notes, mathematical symbols, and scientific notations cannot be represented by Braille letters alone [6]. Moreover, the representation of geometrical concepts is a significant issue in the education of individuals with blindness and visual impairment [7], [8], as these concepts are difficult to grasp without proper tools. Therefore, it is crucial to develop technological tools that support the representation of both letters and shapes to aid in the education of individuals with blindness and visual impairment. Such tools could be paramount in enabling them to learn and understand letters and geometrical concepts more effectively [9].

In this sense, technological advancements, such as E-Braille, provide individuals with blindness and visual impairment with alternatives to traditional written Braille on paper [10]. This innovation enables them to navigate the internet, communicate through text and email, access digital books, and stay connected globally, significantly reducing barriers to information access in unprecedented ways. For example, an electro-mechanical refreshable Braille display (RBD) is a tactile electronic device that connects to other devices like computers, smartphones, or tablets, displaying text in Braille format. RBD works by raising and lowering different combinations of pins in Braille cells to represent the Braille system dynamically in the same device [11]. RBD generates continually changing Braille, offering an ongoing "refreshable" Braille reading experience. This enables individuals with blindness and visual impairment to sense the changing Braille cells, enhancing their ability to interpret text output.

Despite the potential of RBDs to greatly enhance information access for individuals with blindness and visual impairment, there are substantial challenges to overcome, including the

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by Chapman University IRB under Application No. IRB-22-131, and performed in line with the Declaration of Helsinki (as amended in 1989), and the Nuremberg Code.

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[1]The population participating in this study prefer to use the term *Participants/individuals with blindness and visual impairment*. Therefore, for consistency and in respect to our participants, we will use this term in this article when addressing participants/individuals with blindness and visual impairment.

efficient representation of letters and shapes using the refreshable pins, optimization of the number of Braille cells required for representing letters and shapes, and the associated cost, which increases proportionally with the number of Braille cells required [12]. Overcoming these obstacles is crucial for ensuring equitable access to information for individuals with blindness and visual impairment. Acknowledging these significant challenges encountered by individuals with blindness and visual impairment, our research aim is to "design and develop an affordable, multi-functional, and compact RBD capable of representing both Braille letters and fundamental geometric shapes on the same display designed for an educational environment for teaching and learning purposes."

While there are several tactile Braille displays available on the market, most of them are either designed to display Braille letters [13] or stand-alone shapes [14], [15], or just a couple of both [16]. To our knowledge, there are no affordable and compact RBD devices that can represent both Braille letters and shapes by reusing the pins on a single display. The most inexpensive RBD currently available on the market is Orbit20, which costs around \$699 [17]. This is a piezoelectric RBD that has 20 eight-dot Braille cells. Most of the other RBDs cost in the range of \$1000 to \$5000 or more. These devices are expensive and are not primarily developed as educational tools for learning. Therefore, we developed BLISS (Braille Letters and Interactive Shape Screen), a novel, refreshable tactile display capable of simultaneously presenting Braille letters and shapes on a compact and affordable platform to enhance teaching and learning experience among educators and learners with blindness and visual impairment. This cost-effective and portable device can be linked to a computer or laptop, facilitating the instruction of Braille letters and fundamental geometric shapes to individuals with blindness and visual impairment. Considering the different components of our prototype, such as a chassis, piezoelectric benders, Braille pins, a driver board, and a microcontroller, the initial cost of fabricating a unit is estimated at around \$500. We project a cost reduction of 4-5 times with mass production, achieving a unit cost of \$100−\$125. It should be noted that a direct comparison with the cost of currently available products would be unfair, as companies tend to engage in mass production, which could help reduce costs.

However, given the lack of design criteria to display both Braille letters and shapes on the same display, as a first step, we developed a series of 3D-printed sets. These 3D-printed sets are not only tangible mock-ups but also serve as crucial instruments for pilot data collection and refining the final specifications of our tactile display. These sets feature a spectrum of Braille letters and shapes as distinct models with differences between Braille cells and Braille lines.

Consequently, our research aims to explore the following inquiries:

R1) How does varying the spacing between Braille letters and lines in 3D-printed sets impact individuals with blindness and visual impairment's ability to accurately and comfortably discern individual letters and shapes?

R2) When presented with fundamental geometric shapes (e.g., triangle, circle, etc.) using the same spacing as Braille configurations, how effectively can individuals with blindness and visual impairment detect and identify these shapes?

R3) Which specific configuration of spacing between letters, between lines, or both provides the optimal balance for users in terms of ease of reading Braille letters and shape recognition on a Braille display?

To ensure our designs met the practical requirements of individuals with blindness and visual impairment and addressed the research questions, we conducted a user study with eight individuals with blindness and visual impairment. We collected both qualitative and quantitative feedback regarding each set to gain deeper insights into their respective merits, drawbacks, and potential areas for improvement. The key contribution of this paper encompasses:

1) A set of 3D-printed models able to represent both Braille letters and fundamental shapes.
2) Empirical evidence of the strength and improvements of each set.
3) Guidelines to develop a cost-effective RBD capable of showing Braille letters and shapes on the same display using Braille pins.

The overall goal of this research is to provide guidance toward enhancements in RBD technology.

The rest of the paper is organized as follows: Section II provides an overview of the related work. Section III outlines our proposed work. Section IV details the experimental design and results, and Section V addresses the discussion and limitations of the research. Finally, we present the conclusion in Section VI.

II. Related Work

We conducted an extensive literature review to assess the current state of works related to RBD. We divided the related work into four sections based on the type of display.

A. RBDs for Braille Letters

Piezo actuators are the most common technology used in commercially available RBDs [12]. These piezo-actuated Braille cells provide reasonable reliability with moderate mechanical complexity, fast refresh rates, and low power consumption [12]. Nevertheless, as the number of Braille cells increases, it leads to a rise in overall dimensions and higher final product costs [12]. One of the advanced Braille displays, officially supported by Apple [18] and Microsoft [19], is the Humanware Brailliant BI display [20]. This display comes with 40 eight-dot cells and is also available in versions with 32 and 80 cells. A higher price is one of the significant limitations of BI for widespread adoption [20]. The smaller option currently available in the market is the Freedom Scientific Focus 14 Blue 5th generation [21]. This display includes 14 eight-dot cells and advertises durability, meeting military standard 810 G with official support from both Apple [18] and Microsoft [19]. Again, the bottleneck for widespread adoption remains the higher price. Despite its comprehensive features, the device's market price is still high, which limits its accessibility for the average individual with blindness and visual impairment seeking educational tools.

Another RBD aimed at supporting the learning of Braille letters is Annie by Thinkerbell Labs, a self-learning Braille literacy device [13], [22], packed with gamified and interactive content for an engaging learning experience. The other variant for Annie is Polly (US version), created through a collaboration between APH and Thinkerbell Labs [23]. It comprises 6 standard eight-dot Braille cells and 2 enlarged (4.5x) six-dot Braille cells. It features tactile hardware modules tailored for teaching, accompanied by a guiding human voice, minimizing the need for constant supervision. It integrates the Helios suite learning ecosystem for content customization, usage tracking, and performance visualization. However, this display does not provide support for geometric shapes.

Similarly, there are single-cell electromagnetic RBDs that offer stability, durability, and affordability compared to piezoelectric Braille displays [24], [25]. However, single-cell displays are more prone to reading errors [11]. Saikot and Sanim proposed a single-cell RBD with six custom-made electromechanical flapper actuators, offering adjustable cell sizes to cater to learners' preferences [26]. Despite its cost-effectiveness with the use of a single cell, changing the cell size in single-cell RBDs poses a difficulty for individuals with blindness and visual impairment, necessitating comprehensive instructions. Furthermore, the limitation of being unable to display shapes is inherent in single-cell RBDs.

B. RBDs for Shapes

One of the challenges for designing RBDs which remains largely unaddressed, involves the representation of non-textual elements, such as shapes or diagrams [27], [28]. Individuals with blindness and visual impairment typically explore shapes by employing lateral finger motions to detect texture, tracing image contours, and assessing overall shapes using their entire hand [29]. Bhatnagar et al. proposed a study that examined the use of pixel art on pin array displays made from a single sheet of Nitinol for creating tactile graphics, showing that it's clear and understandable for individuals with blindness and visual impairment [30]. However, limitations exist due to the display's small size (27×27 tactile pixels), prompting the need for guidelines to improve the clarity of basic shapes and raising unanswered questions about more complex diagrams and usability for individuals with blindness and visual impairment. Furthermore, questions concerning the minimum gap between distinct shapes, representation of crossing or adjacent lines, creation of textured areas, and the overall usability and comprehension of more intricate tactile diagrams remain unexplored. Leo et al. [31] explored pin-array displays' potential for visual information accessible through touch, which is pivotal for individuals with blindness and visual impairment. The research explored the discriminability of tactile symbols at varying resolutions (3×3 and 4×4) and complexities among distinct participant groups. However, the study faces limitations in determining the most optimal resolution for comprehending basic graphical concepts. Moreover, the research is constrained by its omission of higher resolutions, suggesting the potential for improved accuracy and reduced response time with increased resolutions. A user study on multi-finger haptic rendering of geometric shapes on a 60×60 dot-matrix display is explored in [32]. The study aims to identify the most efficient method for tactile shape perception to determine which rendering method yields the quickest and most reliable recognition performance through touch. Some of the devices that are available in the market that utilize full-page RBDs for representing shapes are Graphiti [14] and HyperBraille F [15]. However, their higher cost renders them unaffordable. Moreover, these interfaces lack the required tangential curves (sliding friction) for the fingers, and there's uncertainty regarding the representation of shapes. One potential solution involves employing smaller refreshable interfaces, aiming to lower costs [33].

Hence, substantial hurdles emerge when designing refreshable displays capable of accommodating both Braille characters within a Braille cell display and shapes while ensuring the ability to trace contours without compromising usability or efficiency [34], [35].

C. RBDs for Braille Letters and Shapes

Despite the importance of learning letters and shapes shown in research, there is limited work that has been done on the development of RBDs that can represent both Braille letters and shapes. Orbit Research developed one such RBD device that displays both letters and shapes on the same board using two different displays [16]. This display comprises 2,400 refreshable pins in a 60×40 array and utilizes Orbit Research's proprietary Braille cell technology. Again, the affordability of the device is the issue. Similarly, American Printing House [36] has recently developed a dynamic tactile device called Monarch in collaboration with Humanware [20] and the National Federation of the Blind (NFB) [37]. The Monarch features an 8-dot Braille keyboard, zoom in/out buttons, direction pads, up/down arrow buttons, and a 10-line by 32-cell electromagnetic RBD and is capable of rendering multiple lines of Braille and tactile graphics. The device is in the beta test phase, and the price prediction is relatively high. The new cell technology used in this device is developed by DOT Inc. [38].

D. Braille Displays to Represent Letters and Shapes

On the other hand, there are vibrotactile displays such as Optacon [39] and V-Braille [40] that offer differentiated vibrations within the contact region or fingertip, allowing for improved perception of detailed contours. However, representing Braille characters on such displays might pose a challenge, demanding a considerable learning curve as users must adjust to interpreting vibrations as textual or graphical information [41].

Overall, there are continuous efforts underway to develop a cost-effective refreshable tactile display. However, there are still the following limitations. Firstly, the high-density pin array emulating the authentic experience of reading traditional Braille books brings a higher cost of the Braille displays, as expenses rising with each additional cell [12]. Secondly, there is limited literature and guidelines on RBDs that display both Braille letters and shapes by reusing the same pin matrix of the display. Lastly, it is unclear how to design an RBD pin array that could

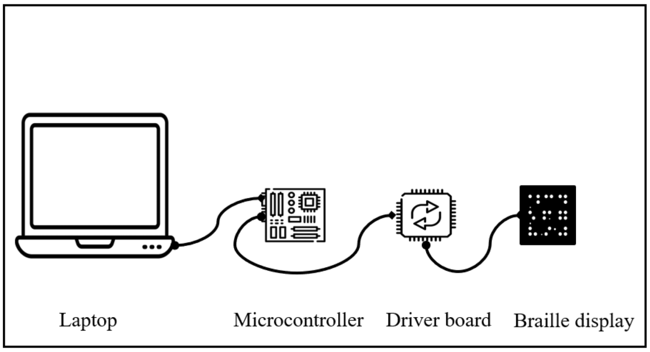


Fig. 1. Illustration of the workings of BLISS prototype.

be used as a learning tool for inexperienced learners instead of reading books or documents. Hence, there is an acute need for the development of RBD as an educational tool that will be beneficial to both educators and individuals with blindness and visual impairments for learning purposes. Thus, a redesign of the RBDs is needed to fill this literature gap, which will not only reduce the number of Braille cells to represent both Braille letters and shapes effectively but also lower the cost of these displays as an educational tool. Keeping this in mind, we strive to develop a cost-effective and compact RBD that is capable of displaying both Braille letters and shapes effectively by reusing the Braille pins of the same display as an educational tool.

III. Proposed Work

A. BLISS: Braille Letters and Interactive Shape Screen

Our research is driven by the core objective of exploring efficient methods for displaying Braille letters and shapes using a novel device called BLISS. BLISS is a compact, refreshable tactile display designed to present Braille letters and shapes (Fig. 1). This innovative platform aims to be affordable and effective for early education, particularly benefiting individuals with blindness and visual impairment. The BLISS prototype consists of a chassis, piezoelectric benders, Braille pins, a driver board, and a microcontroller. The approximate dimensions of this device are 8 cm × 4.5 cm × 2.5 cm.

Given that the average functional English word typically comprises around 3.13 letters, while content-rich words average around 6.47 letters [42], we aim to develop a display capable of simultaneously representing six letters using 3×2 Braille cells. Letters will be read from left to right, progressing from the top row to the bottom [43].

To display the letters and shapes, BLISS uses piezoelectric bending actuators to raise pins and form Braille letters and shapes. Our prototype setup involves a laptop, a microcontroller, and a tactile display. The BLISS device is controlled by a laptop, a microcontroller, and a piezo driver board.

The working of the BLISS is described as follows (Fig. 1): 1) The user inputs letters (using the keyboard) or shapes (using a custom web app) via a laptop; 2) A microcontroller interprets these signals received from the input and transmits them to piezo drivers; 3) These piezo drivers then activate the piezoelectric benders, causing the pins to move above the chassis and display the entered letters or shapes (Fig. 2).

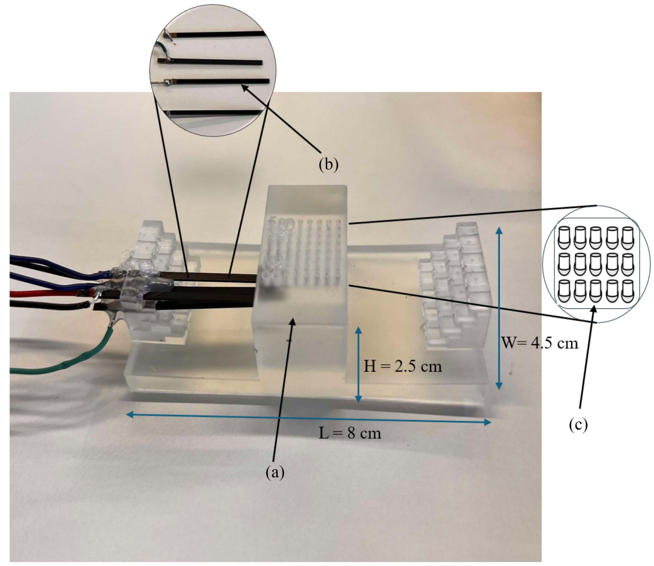


Fig. 2. BLISS prototype. (a) Chassis. (b) Piezoelectric benders. (c) Braille pins.

The tactile display comprises piezo drivers responsible for actuating piezoelectric benders. These piezoelectric benders, attached to pins, facilitate their movement above a solid chassis (Fig. 2).

Given the limited guidelines for developing RBDs to display Braille letters and shapes, the first step in this research is to find an optimal configuration of BLISS to represent Braille letters and shapes effectively in educational settings to teach Braille letters and geometric shapes. To address this, we iteratively designed 3D-printed sets, varying the horizontal and vertical spacing between Braille cells and the pin arrangement within each cell (Fig. 5). In the subsequent section, we provide an in-depth discussion of the detailed design aspects of these 3D-printed sets, such as the specific variations in spacing and configuration we are testing.

B. Design of 3D-Printed Sets

Although the design requirements for displaying Braille letters have been clearly defined [43] (i.e., Braille display dot diameter: 1–1.6 mm, dot displacement: 0.2–0.5 mm (at least), dot pitch: 2.2–2.8 mm, dot tactile force: minimum 100 mN, refresh frequency: minimum 1 Hz, and operating voltage: less than 12 V). To the best of the authors' knowledge, there are no existing standards for displaying shapes. We designed and developed 3D-printed four unique sets of BLISS models. Each set was printed twice, once with letters and once with shapes. We maintain consistent dimensions for Braille dots (1.5 mm diameter, 0.2 mm displacement, 2.5 mm pitch) across all models [43]. The resin 3D printer is employed to fabricate all the 3D-printed models, specifically using the Prusa SL 1 resin printer, and their designs were created using Fusion 360.

We chose a six-letter phrase for the letter display. A 3D-printed sample representing letters is shown in Fig. 3. Similarly,

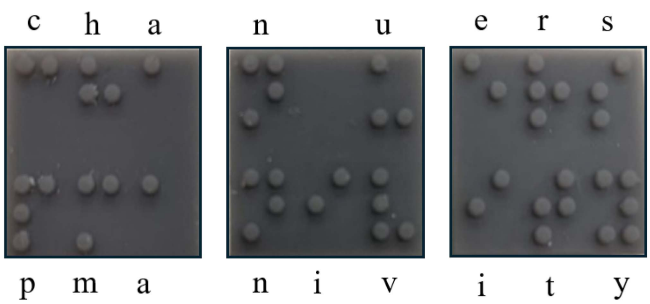


Fig. 3. Sample of 3D-printed letters using set 1 configuration.

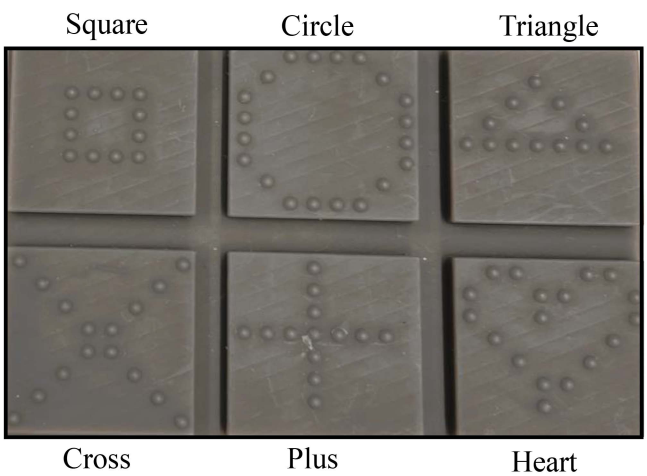
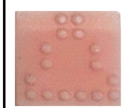
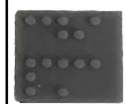
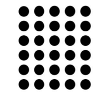
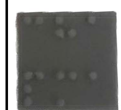
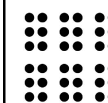
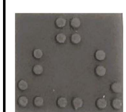
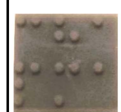
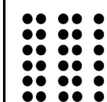
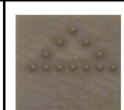
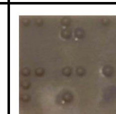
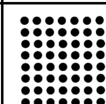


Fig. 4. Sample of 3D-printed shapes using set 4 configuration.

TABLE I
SAMPLES OF 3D PRINTED SHAPES AND LETTERS

Model Name	Configuration Description	Shape Example (Triangle)	Letter Example (chapma)	Configuration
Compact-Set 1 (6 x 6)	Six-cell braille display with no spacing between cells or lines			
Standard-Set 2 (6 x 6)	Six-cell braille display following braille standards			
Removing spacing-Set 3 (6 x 6)	No spacing between braille lines, standard Braille cell spacing.			
Extra pins-Set 4 (8 x 8)	Pin matrix with extra pins between cells and lines			

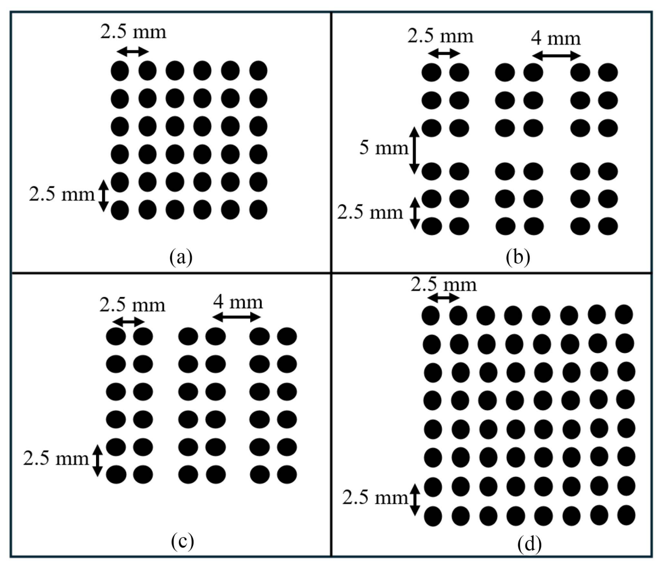


Fig. 5. Comparative illustration of 3D-printed sets. (a) Compact-set 1, (b) standard-set 2, (c) removing spacing-set 3, and (d) extra pins-set 4 showcasing variations in Braille cell spacing and line spacing for low vision perception assessment.

we chose six fundamental geometric shapes, such as square, circle, triangle, cross ('X'), plus ('+'), and heart for the shape display. Fig. 4 shows 3D-printed samples of shapes. The rationale behind this shape selection is rooted in capturing fundamental geometric concepts, as explained as follows:

- *Lines:* the 'square' and 'triangle' serve as primary representations of straight lines; the square delineates right angles and uniformity, while the triangle offers varied angles within a closed form.
- *Intersection:* the 'X' and '+' shapes signify intersections, with the 'X' embodying diagonal intersections and the '+' symbolizing perpendicular ones.
- *Curves:* The 'circle' was incorporated to present a perfect curve devoid of edges or vertices.
- *Combination:* the 'heart' shape combines both straight lines and curves.

This curated selection ensures that individuals with blindness and visual impairment are exposed to a broad spectrum of geometric constructs, ranging from simple to intricate forms. Table I shows the samples of the 3D-printed shapes and letters, along with detailed information about each set.

- *Compact-Set 1:* This set represents the most compact design. It has a 6×6 pin matrix, and Braille cells are directly adjacent to each other without any intercellular spacing or separation between lines, as shown in Fig. 5(a). The standard pitch of 2.5 mm between Braille pins is retained. We hypothesize that the continuous arrangement of pins could effectively represent shapes and provide a clear line for the index finger, enhancing tactile perception.
- *Standard-Set 2:* This set represents a 6×6 pin matrix adhering to Braille standards (Fig. 5(b)). In standard Braille, the distance between corresponding dots in adjacent cells typically ranges from 6.1 mm to 7.6 mm, with an approximate average of 6.5 mm used in our design [44]. Additionally, the distance between corresponding dots from one cell

TABLE II
PARTICIPANT DEMOGRAPHICS

Participant	Sex	Age (Yr.)	Age of onset of blindness/ visual impairment (Yr.)
#1	M	63	40
#2	F	23	3 months
#3	F	63	38
#4	M	55	53
#5	F	48	43
#6	F	47	12
#7	F	42	34
#8	F	29	birth

directly below ranges from 10.0 mm to 10.2 mm, with our choice being 10mm [44].

- *Removing spacing-Set 3:* This set has a 6×6 pin matrix. This model preserves the spacing between Braille cells (4 mm) to maintain the readability of Braille letters, but the spacing between Braille lines (2.5 mm) is replaced with additional pins. This adjustment aids in shape detection as the finger can track lines more effectively compared to standard Braille configurations, as shown in Fig. 5(c).
- *Extra pins-Set 4:* This set utilizes an 8×8 pin matrix. The cell and line spaces are replaced by extra pins, as shown in Fig. 5(d). The distance between each pin is 2.5 mm. We hypothesize that the extra pins will ease the representation of shapes while fully rising and lowering to keep the 2×3 cell to represent Braille letters, acting as spaces.

IV. EXPERIMENTAL EVALUATION

This section outlines the experimental design and results of the user evaluation.

A. User Evaluation

To address the research inquiries, we assessed each 3D-printed set, considering both qualitative and quantitative measures. This includes analysis of user feedback, gauging comprehension, and evaluating user comfort levels when working with our different 3D-printed sets.

1) Study Participants: Eight individuals with blindness and visual impairment (six female and two male) were recruited for this study. Participant age groups were not pre-selected. The participants' mean age was 46.25 years, with a standard deviation of 14.63 years (Table II). Out of 8 participants, 75% were right-handed, 25% were left-handed, and within both groups, 25% utilized both hands for reading Braille. The average age of blindness/visual impairment onset among the participants was 27.5 years. All participants used Braille as their primary literacy medium. The experiments were conducted in collaboration with a Braille institute. Each participant had been engaging in Braille studies for a duration of 1–2 years. The experimental procedure received approval from the Institutional Review Board (IRB), and all participants provided informed consent for their involvement in this research.

2) Study Design and Procedure: We followed a within-study approach where all participants interacted with the four 3D-printed sets of Braille models assigned in random order. There was no specific training phase; instead, a testing phase lasting 25–30 minutes was implemented. The participants were not informed in advance about the shapes and letters that would be presented to them. Each set is separated into two subsets: one illustrating 3 variants of six Braille letters Fig. 3 and 6 variants for six different shapes Fig. 4 on each 3D-printed set. In total, each participant interacted with 36 variants of 3D-printed sets.

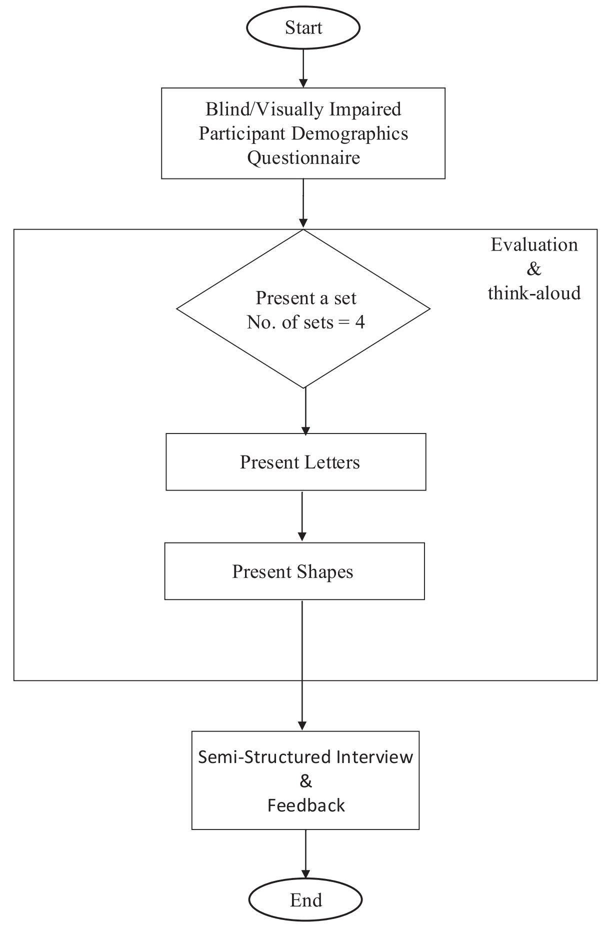


Fig. 6. Experimental flowchart.

Participants were seated at a designated table, and one member of the research team provided each of the sets in the correct orientation. Fig. 6 presents the experimental flowchart, outlining the critical stages of the study. We considered a blocking design where participants are divided into blocks, and each block experiences the conditions in a different order without repetition. We then requested participants to identify the shapes by interpreting the Braille pins' contours presented in the four configuration sets. Next, we presented them with the Braille letters for identification. Participants had the discretion to use either their Braille index finger or both fingers for reading. For each set, participants were prompted to think aloud (i.e., participants think out aloud while performing a given task or recall thoughts immediately following the completion of that task.) to get feedback while they were interacting with each of the set [45], and provided their best guess of what shape or letter was in the set. Think-aloud sessions were audio-recorded during the testing phase. Participants were afforded multiple opportunities to interpret Braille letters/shapes correctly before receiving assistance.

The study spanned three sessions. The first two sessions focused on exploring the impact of spacing in recognizing letters and shapes, while the third one focused on exploring the impact of the pin configuration. Concluding the sessions, we conducted a semi-structured interview to get feedback on how to improve the sets.

3) Data Analysis: To evaluate the effect of spacing and pin configuration in recognizing letters and shapes, we computed the percentage of correct letter/shape identifications by our participants. We formulated a recognition accuracy as in (1):

$$\text{Recognition Accuracy } (\%) = \left(\frac{\text{Number of correct identifications of letter/shape}}{\text{Total numbers of participant}}\right) \times 100 \quad (1)$$

The participant feedback from the think-aloud and semi-structured interviews was transcribed and analyzed using qualitative techniques. We particularly group participant feedback in categories representing challenges they faced per set and suggestions for improvements. We used a transcription service to transcribe audio recordings from all the sessions (think-aloud and semi-structured interviews) for analysis. The transcription covered 8 interviews that lasted about 224 minutes in total. We also listened to the audio again to correct the transcripts when necessary. We applied reflexive thematic analysis (RTA) techniques [46], [47] to analyze the transcripts. One researcher used an inductive approach to code the transcripts and find common themes. The whole team then discussed the themes. The final themes included difficulties in recognizing some shapes and recommendations for enhancing current sets. We also incorporated feedback from several participants regarding the sets.

B. Results

Overall, all participants were able to interact with all the 3D-printed sets, and they provided feedback on each of them. In the following sections, we presented and discussed the recognition accuracy of each set per shape and letter. We also compared the recognition accuracy between the 6×6 and the 8×8 pin configuration.

1) Spacing Impact on the Recognition of Shapes and Letters: We discovered that participants had more trouble identifying letters using the Compact-Set 1 version (43.85%), followed by the Removing spacing-Set 3 (51.62%), and the best one was the Standard-Set 2 (61.43%) for the 6×6 models (Table III). These results showed the importance of adding space between letters to ease their identification. However, in terms of shape recognition the worst set for detecting shapes was Removing spacing-Set 3 (56.25%), followed by Standard-Set 2 (64.58%), and the best one was the Compact-Set 1 (71.88%) for the 6×6 models as shown in Table III. These results show that for representing shapes, it is better not to have spaces between lines or cells. On average, participants recognized 64.24% of the shapes and 52.30% of the Braille letters independently of the spacing of the sets for the 6×6 models (Table IV).

TABLE III
ACCURACY COMPARISON FOR SHAPES AND LETTERS ACROSS FOUR 3D MODEL SETS

Model configuration	Accuracy for detection of shapes (%)	Accuracy for detection of letters (%)	Avg. accuracy for detection of both shapes & letters (%)
Compact-Set 1	71.88	43.85	57.87
Standard-Set 2	64.58	61.43	63.00
Removing Spacing-Set 3	56.25	51.62	53.94
Extra pins-Set 4	81.25	85.67	83.46

TABLE IV
ACCURACY COMPARISON BETWEEN 6×6 (AVERAGE) AND 8×8 PIN CONFIGURATIONS

Pin configuration	Accuracy for detection of shapes (%)	Accuracy for detection of letters (%)	Avg. accuracy for detection of both shapes & letters (%)
6 x 6	64.24	52.30	58.27
8 x 8	81.25	85.67	83.46

The findings highlight a trade-off between spacing and the identification of shapes and letters (Table III). On one hand, spaces are essential for letter identification, but they create distortions in the contours of shapes. Conversely, insufficient space for shapes leads to ambiguity in distinguishing the start and end points of letters. Hence, the pin configuration should also be considered in the design process. To handle these issues, we propose an innovative approach by including an 8×8 pin configuration in our design process. We observe that participants recognized 81.25% of the shapes and 85.67% of the Braille letters with an 8×8 pin configuration as shown in Table IV.

2) Pin Configuration Impact on the Recognition of Shapes and Letters: When comparing the average 6×6 pin configurations with the 8×8 pin configuration (i.e., Extra pins-Set 4), we found that, on average, adding an extra pin set is 24.14% better in recognition of both shapes and letters than the 6×6 configuration. Particularly, the detection of letters improved by 33.37%, and the detection of the shape by 14.92%, on average (Table IV).

We found that participants found it easier to recognize shapes with smooth curves such as circle and heart, with the additional pins in the 8 x 8 pin configuration, despite some shape curves being quantized. This could be partially explained by filling the rows and columns with extra pins, which provides participants with a better perception of continuous lines compared to other configurations without extra pins. Overall, these results show that adding one refreshable extra pin that allows spaces for letters and an extra pin for shapes improves the recognition of both letters and geometric shapes.

3) Exploring the Relation Between Geometric Concepts and Configuration Structures: Fig. 7 shows a comparison of recognition accuracy of shapes (%) between the best 6×6 model (Standard-Set 2) vs. the 8×8 model, and we visualized the user assessment of shapes by employing a confusion matrix. The specifics of this matrix are outlined in Tables V–VIII. In these tables, the color coding (red) signifies the accuracy level for

TABLE V
SHAPES CONFUSION MATRIX-SET 1

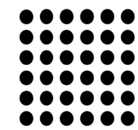
		Predicted Class							Set 1 Configuration
		□	◯	△	×	+	♡	Other	
Actual Class	□	100%	0	0	0	0	0	0	
	◯	0	37.5%	0	0	0	0	62.5%	
	△	0	0	50%	0	0	0	50%	
	×	0	0	0	100%	0	0	0	
	+	0	0	0	0	0	0	100%	
	♡	0	0	0	0	0	0	100%	

TABLE VI
SHAPES CONFUSION MATRIX-SET 2

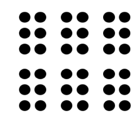
		Predicted Class							Set 2 Configuration
		□	◯	△	×	+	♡	Other	
Actual Class	□	100%	0	0	0	0	0	0	
	◯	0	62.5%	0	0	0	0	37.5%	
	△	0	0	12.5%	0	0	25%	62.5%	
	×	0	0	0	100%	0	0	0	
	+	0	0	0	0	100%	0	0	
	♡	0	0	0	0	0	12.5%	87.5%	

TABLE VII
SHAPES CONFUSION MATRIX-SET 3

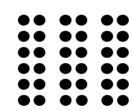
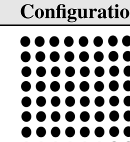
		Predicted Class							Set 3 Configuration
		□	◯	△	×	+	♡	Other	
Actual Class	□	100%	0	0	0	0	0	0	
	◯	0	62.5%	0	0	0	0	37.5%	
	△	0	0	0 %	0	0	0	100%	
	×	0	0	0	100%	0	0	0	
	+	0	0	0	0	37.5%	0	62.5%	
	♡	0	0	0	0	0	37.5%	62.5%	

TABLE VIII
SHAPES CONFUSION MATRIX-SET 4

		Predicted Class							Set 4 Configuration
		□	◯	△	×	+	♡	Other	
Actual Class	□	100%	0	0	0	0	0	0	
	◯	0	75%	0	0	0	0	25%	
	△	0	0	75%	0	0	0	25%	
	×	0	0	0	100%	0	0	0	
	+	0	0	0	0	87.5%	0	12.5%	
	♡	0	0	25%	0	0	50%	25%	

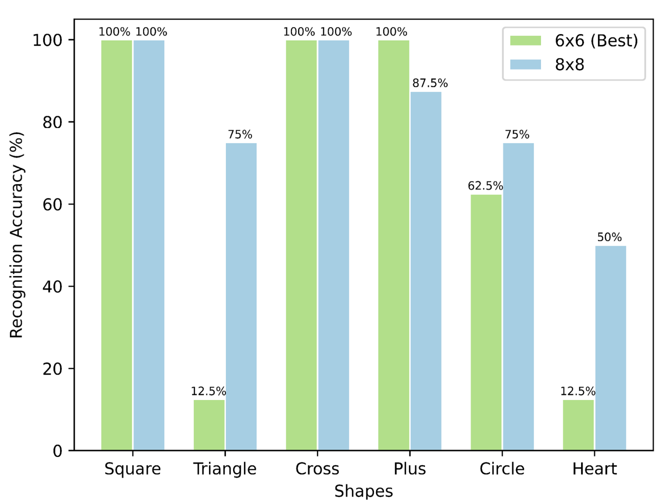


Fig. 7. Comparison of recognition accuracy of shapes (%): 6×6 model (best) vs. 8×8 model.

each shape class across four distinct confusion matrix sets, with 100% representing the highest accuracy and 0% indicating the lowest accuracy.

In confusion matrix set 1, all participants accurately predicted both the square and the 'X'. However, the accuracy for predicting the circle was only 37.5%. Notably, 62.5% of participants misidentified the circle as a diamond. For the triangle, 50% of participants predicted it correctly, while 20% misidentified it as a tent, and 30% as an inverted V. None of the participants in set 1 correctly identified the '+' and heart shape. In confusion matrix set 2, all participants accurately predicted the square, 'X', and '+' shapes with 100% accuracy. The circle was correctly identified by 62.5% of participants, while 37.5% reported that they could not discern it as a shape. The triangle and heart shapes were correctly identified by only 12.5% of participants. Specifically, 50% of participants misidentified the triangle as a key, 25% of participants misidentified the triangle as a heart, and 12.5% were unable to recognize it as a shape. Similarly, 87.5% of participants did not recognize the heart as a shape. In confusion matrix set 3, square and 'X' are predicted with 100% accuracy. The circle is correctly identified by 62.5% of participants, while 37.5% did not identify it as a shape. '+' and heart shapes are accurately recognized by 37.5% of participants. However, 62.5% of participants could not identify '+' correctly, and 50% of participants mistakenly perceived the heart as a star, with 12.5% unable to identify the heart shape. None of the participants in set 3 correctly identified the triangle shape. In confusion matrix set 4, all participants correctly identified the square and 'X'. 87.5% of participants correctly identified '+', while 12.5% perceived it as a railroad track. For the circle and triangle, 75% of participants correctly identified these shapes. However, 25% of participants did not recognize both the circle and triangle as shapes. Only 50% of participants correctly identified the heart, while 25% thought it was a triangle and another 25% did not recognize it as a shape.

The results show that both the square and the 'X' shapes were consistently recognized with 100% accuracy across all sets. In contrast, the heart shape was the most difficult to recognize (25% in the 6×6 (on average) and 50% in the 8×8). This result shows that it becomes increasingly challenging to recognize as the shape incorporates more lines, intersections, curves, or combinations thereof. Moreover, the low recognition accuracy of the symbol, such as the heart, could be due to factors beyond its shape and arrangement, such as symbol familiarity. While the heart symbol is a commonly recognized symbol among sighted individuals, it may not be as familiar for people who are blind, especially those who are congenitally or early blind [48].

Comparing by type of pin configuration, we found out that representing a triangle is better if we remove the space and add more pins in between. There is an improvement in recognition of triangle by 54.17% in 8×8 configuration compared to 6×6 (average) configurations. In this case, having a continuity line is required to figure out the shape. Similarly, for the circle, the 6×6 arrangement of pins creates confusion about whether the contour represents a straight, small line or a continuous curve. The recognition of the circle in the 8×8 pin configuration shows an improvement of 20.84% compared to the 6×6 (average) configurations. Overall, removing spaces between cells and lines by adding extra pins improves the recognition of shapes.

4) Participant Feedback and Suggestions: Qualitative feedback from participants revealed distinct challenges and ease associated with recognizing Braille letters and specific shapes. In terms of Braille letters, participants recognize that each individual pin should be improved by making them more rounded; a few participants observed:

"The pins lack sufficient roundness."

Moreover, all of them agree that spacing between letters is needed, especially on the 6×6 sets, as one participant said:

"The spacing is necessary for letters."

They also expressed the requirement for extra training to get used to that type of spacing. Additionally, there were remarks concerning the appearance of the shapes. For instance, the triangle was tricky for participants to discern if the Braille dotted lines deviated even slightly from a straight path. The constraints of the 6×6 Braille display rendered it inadequate for representing a triangle. However, the 8×8 configuration accommodated the shape better. The circle in the smaller configuration was usually confused with other shapes, such as diamonds, given that the curves were confused by lines.:

"For [set 1], the circle looks more like a diamond."

Also, participants suggested that the heart shape required additional Braille dots to depict its central indentation accurately.

Overall, these results highlight the importance of providing extra pins to the users to ease the recognition of shapes while conserving the predefined design of Braille letters to speed up the letter recognition.

V. Discussion and Limitations

We experimented with four different configuration sets on eight individuals with blindness and visual impairment. To answer R1 about spacing, we found that the spacing between Braille letters and lines in 3D-printed sets significantly affects the ability of individuals with blindness and visual impairment to accurately and comfortably distinguish individual letters and shapes, as discussed in the results. Participants had difficulty distinguishing individual letters and shapes with a model with compact Braille cells with no spacing between cells or lines and with a model with no spacing between Braille lines. The critical factors influencing letter recognition encompass the ability to accurately detect both the number of dots (dot numerosity) and their relative placement within a cell.

Similarly, to answer R2 about geometric shapes, we observed that the identification of geometric shapes improved when using a set with Braille cells with continuous lines and extra pins in the horizontal and vertical directions. Overall, our findings indicate that, apart from fundamental shapes, there is a tradeoff where shapes with more lines, intersections, curves, or their combinations require a greater number of Braille dots for enhanced accuracy, but this comes at the expense of a potentially costlier display with larger pin configurations. However, displaying larger and more complex shapes is beyond the scope of this work and represents its limitation. Conversely, for fundamental geometric shapes such as the square, enlarging the display and increasing the dot count did not significantly improve recognition, affirming that they can be effectively represented with fewer Braille dots.

Our findings highlight the vital role of involving individuals with blindness and visual impairments since the earlier stage of the design and development process of RBD [49]. Even a small sample of direct feedback from final users makes a great difference in the acceptability and success of a product; in our case, gathering direct feedback from our participants allowed us to propose a novel setup configuration of pins before developing the final prototype version. This will lead to a second phase of experiments to achieve an accurate representation of both letters and shapes in a confined Braille display space. These results are pivotal, as they contribute meaningfully to the ongoing discussion surrounding assistive technologies. We present a model that seamlessly integrates both basic shapes and Braille letters within the same display.

To design an affordable and compact RBD, we initially explored the 6×6 configuration due to its cost-effectiveness and potential portability. To address R3 about specific configuration, our findings suggest that the tightly packed nature of the 6×6 Braille display, especially with no spacing between Braille letters or lines, hampers the distinguishability of letters for individuals with blindness and visual impairment. While this configuration can adequately present fundamental shapes such as square, it falls short in letter representation and more complex shapes. In contrast, our study advocates for the 8×8 configuration as a superior alternative. In this configuration, all 64 pins can be utilized for shape depiction, while a subset of 36 pins can represent six letters. This configuration adheres to conventional Braille spacing: 2.5 mm between cells and 5 mm between lines [44]. The proposed design is adaptive; while all pins rise for shape display, only select pins ascend for letter representation, offering a versatile multi-mode operation yet a clear tactile experience with pins' reusability within the same display.

While the achievement of our objectives is noteworthy, we acknowledge several limitations, starting with our small sample size ($N = 8$), necessitating future research to incorporate more extensive and more diverse samples to enhance the generalizability of the findings. However, for research focusing on individuals with blindness and visual impairment, it is generally acceptable and common to recruit a small user sample [50]. To circumvent this limitation in the current study, we have collected a rich blend of qualitative and quantitative data to garner more nuanced insights. Moreover, our model's evaluation was limited to a subset of letters and shapes. While diverse, future iterations of this work should encompass a broader array of symbols to substantiate our understanding further.

Additionally, we recognize the importance of a well-described participant population; however, we cannot include this information in the paper due to privacy concerns. In future studies, we will ensure a more detailed description of the participants, including the etiology (cause) of their blindness/visual impairment and the presence or absence of residual vision. This will allow for a more nuanced understanding of how haptic and tactile perception might be influenced by the level of visual disability. As future work, we acknowledge and add that we are actively exploring ways to increase the sample size for future studies. This involves collaborations with other Braille institutions or expanding the recruitment criteria. Furthermore, we acknowledge that the possibility of order effects exists for the current study. However, we have taken steps to mitigate this to some extent. In future studies, we will implement a counterbalanced design where the order of conditions is randomized across participants to mitigate potential order effects. This will involve dividing participants into groups and presenting the four sets in a pre-determined order that balances out any potential order effects. Lastly, we will incorporate questions about participants' familiarity with specific symbols, including the heart symbol. This additional data will allow us to investigate the influence of symbol familiarity on recognition accuracy. As our research goal was not to generalize the results but to provide insights on the optimal configuration of an RBD, the results reported in this paper are valuable and are an essential first step to developing affordable RBDs that represent both Braille and shapes on the same display.

VI. Conclusion

In summary, this research explores the design space for pin configurations using 3D-printed sets to develop an RBD called BLISS. BLISS features a unique configuration of Braille cells that can accommodate up to six letters at a time and geometrical shapes by reusing the Braille pins within the same display, resulting in a versatile, compact, and economically viable educational tool for educators and individuals with blindness and visual impairment. The optimal specifications, such as size, Braille cell spacing, and pin configuration for BLISS, were determined by fabricating and evaluating 3D-printed sets. The study found that while the conventional spacing to represent six letters is sufficient for Braille letters, it is not enough to represent shapes using the same format accurately. Hence, a novel design is proposed that uses a pin configuration to raise the extra pins to represent shapes and lowers them for Braille, providing dual-mode operation while maintaining a compact and cost-effective configuration.

The addition of graphical elements representing graphs, charts, and trends to the Braille display is paramount for future research, potentially enabling younger individuals with blindness and visual impairment to perceive the significance of Braille over auditory systems alone. This extension is vital, especially as we move toward a more technologically advanced era where the design of RBDs is becoming more versatile and cost-effective.

We are optimistic that with continued research and development, the integration of such graphical elements will become standard, allowing for increased accessibility and enhanced learning experience for individuals with blindness and visual impairment, including those in low-income groups, providing them with a more profound and independent exploration of the information world. Despite the inherent limitations, our work lays down the foundation for a future where enhanced and accessible Braille displays become a norm, redefining the learning landscape for individuals with blindness and visual impairment by intertwining Braille with graphical elements, thereby narrowing the accessibility gap significantly.

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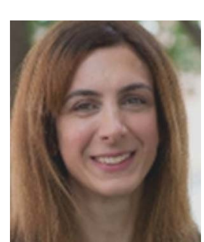

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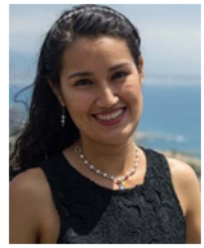

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