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A Solution Proposal for the Modernization of the Braille Alphabet Teaching-Learning

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Abstract: Visually impaired individuals face challenges during their learning process, often due to the lack of necessary resources to acquire basic skills such as literacy and access to information tailored to their needs. Therefore, ensuring that they learn Braille early is crucial, as this will guarantee their access to knowledge and enable them to better integrate into society. Not only does it provide them with more communication channels, but it also equips them with tools to navigate the workforce. This article presents a low-cost technological solution for teaching the Braille alphabet to blind children through an electronic keyboard. The device features buttons printed using a 3D printer, each representing a letter of the alphabet in Braille, resembling domino tiles. When a button is pressed, it activates a speaker that pronounces the selected letter aloud. The electronic device is complemented by a mobile application that supports the teacher. This proposal was developed in response to a need that arose at the Centro de Atención Múltiple No. 50 (CAM) in Mazatlán, Sinaloa, Mexico, due to the enrolment of a girl (four years old) with total blindness. The school lacks sufficient resources to support the student in her learning process, prompting the development of the electronic keyboard as a teaching aid, which was donated to CAM Mazatlán No. 50.

Keywords: 3D modeling; 3D printing; Arduino; Braille language; teaching-learning process

1 INTRODUCTION

People with visual impairment face challenges during their learning process because many do not have the necessary resources to learn basic skills such as literacy and access to information adapted to their stimuli. Therefore, it is of utmost importance to ensure the learning of the Braille language at an early age; this will guarantee their access to knowledge and allow them to develop in a better way in society, not only giving them more ways of communication but also providing them with tools so they can develop in a work environment. The Mexican National Institute of Statistics, Geography, and Informatics estimates that in Mexico, there are approximately 2 million 719 thousand people with visual impairment and more than 415,800 people with blindness [1]; also, Mexico is among the 20 countries with the highest number of people affected by visual impairment and blindness.

Throughout history, blind people have sought to be able to read, write, walk in the street, and be independent in many ways. It was not until 1829 that the pedagogue Louis Braille designed a reading and writing system suitable for blind people, thanks to the effort and adaptive capacity of the human being to find solutions to apparently unsolvable problems, receiving the name of Braille system. The Braille system is known worldwide as the alphabet for the blind par excellence.

Learning is one of the first and most important things we do when we start growing up; for blind people, it is no exception. However, learning Braille has specific difficulties that are important to know. One of its main difficulties at the time of learning is the speed at which the reader assimilates the words; the Braille language is purely sensory; it requires special attention to each letter individually, which makes it slower to read, reaching between 150 to 200 words per minute for an experienced reader. This leads the reader to misinterpret a text, confusing the letters because of the similarity in how they are represented, making learning the Braille alphabet a fundamental part of the development of communication skills of a person with visual impairment. Given the problems encountered, the need arises to develop an electronic device capable of assisting in learning Braille and facilitating the teaching of Braille to children with visual impairment.

In the *Centro de Atención Múltiple* (CAM) No. 50, a public institution for special education in young kids in the city of Mazatlán, Sinaloa, there is a case of an infant with blindness, who does not have basic knowledge such as how to read or write. The CAM does not have sufficient resources to meet the child's learning needs. Likewise, they do not have trained personnel to instruct her since teaching these children requires much attention, a well-thought-out methodology, and constant feedback and evaluation. It is a challenge for the teachers who attend to several groups with dozens of children during their workday.

Research Problem

Despite notable advances in assistive technologies, early Braille literacy in low-resource educational settings remains substantially constrained by the absence of affordable tools that integrate both tactile exploration and systematic teacher-guided evaluation. Existing devices tend to be prohibitively expensive, technologically complex to reproduce, or limited in pedagogical functionality. This is particularly true in their inability to provide reliable mechanisms for monitoring and assessing student learning progress.

Research Questions

RQ1: Does the proposed Braille teaching keyboard improve the accuracy with which children identify Braille characters?

RQ2: Does the integrated evaluation app provide teachers with reliable performance metrics?

Measurable Objectives

O1: Quantify the percentage of correct letter identifications after guided practice.

O2: Measure time to identify characters.

O3: Compare performance against a control group.

O4: Assess usability (SUS or adapted scale for special education teachers).

This proposal is designed to provide practical support to the CAM in teaching Braille. By leveraging Information and Communication Technologies (ICT), we aim to enhance Braille literacy among Mexican children and support institutions like the CAM in their important work.

This work is structured as follows: Section 2 presents state of the art regarding the electronic devices that have been used for teaching Braille language to both children and adults, particularly describing their methodology, the technological platform on which they are developed, their design, their functionality, and the area where they have been applied. Section 3 systematically describes the whole process of analysis, design, and development of the prototype that supports teaching the Braille code. Section 4 presents an experimental evaluation, and Section 5 contains the final ideas on the project carried out, significant contributions of the research, and ideas and improvements for future work.

2 STATE OF THE ART

A broad range of assistive technologies has been proposed to support learning, mobility, and autonomy in blind and visually impaired individuals. Early work such as [2] presents a hardware-software device capable of interpreting edited text and dynamically generating tactile Braille relief, offering users a practical means of accessing written information. Similarly, [3] details the systematic development of a Braille board and companion mobile application to help teachers evaluate student performance through a user-friendly interface. Beyond literacy, multimodal interaction has also been explored; for example, EmoSons [4] enables blind or autistic children to create and explore music through a tactile Arduino-based surface processed via the Processing environment. Complementing these approaches, the "Catalog of Accessible Apps" described in [5] compiles 92 Android applications optimized for low-vision and blind users, highlighting the importance of accessible mobile ecosystems.

A significant body of research addresses mobility and environmental perception. The prototype in [6] employs an HC-SR04 ultrasonic sensor, solar-powered Arduino Mini Pro, vibration alerts, and audio feedback to detect obstacles through a wearable cap-mounted system. Likewise, [7] introduces an electronic color-detection device using signal processing and auditory cues to help users identify colored objects. Additional systems focus on structured interaction and practice: [8] proposes a six-button Braille layout controlled via a mobile application for teacher-assigned exercises, while [9] presents an auditory memory game that promotes cognitive engagement and familiarization with electronic devices.

On the other hand, several studies emphasize tangible interaction for Braille literacy. The didactic use of Escornabot [10] employs RFID-embedded instruction cards labelled in Braille to strengthen logical reasoning and spatial navigation skills. In [11], the B-Box system uses RFID cards to introduce letters and requires students to reproduce Braille patterns via a 2 × 3 button array, emphasizing pattern recall rather than tactile exploration. More advanced prototypes include the servo-based dynamic Braille cell device in [12], implemented in Peruvian CEBE centers, which students found easier to use than traditional materials. Mobility-assistance work continues in [13] with an intelligent cane integrating ultrasonic sensing, vibration feedback, GPS tracking, and portable power, and in [14] with a configurable sensor-equipped cane-glasses kit linked to a mobile app for improved navigation and access to public transport.

Efforts to address the decline in Braille literacy have yielded additional solutions. Braille Blocks [15] allows sighted parents to support blind children using block-based Braille patterns evaluated through a camera-enabled web application. Likewise, Hiperión [16] offers automated conversion of digitized Braille into Spanish text to streamline classroom assessment. Braillet [17], a microprocessor-controlled tactile board with 30 Braille cells, provides read/write modes, auditory guidance, and motivational feedback, demonstrating positive effects on early Braille learning.

Recent work highlights the role of ICT during COVID-19 disruptions. The device presented in [18] translates mathematical symbols into Braille via a web-connected platform designed using Design Thinking principles (portability, usability, adaptability). Further improvements in mobility technologies are seen in [19], where a forearm-mounted tiflotechnological device consolidates sensors within a single wearable form factor, and in [20], which introduces a mathematics-teaching tool that improves task performance and aligns with inclusive education policies. Collectively, these studies underscore the growing importance of low-cost, interactive, and ICT-driven assistive technologies for enhancing educational access, literacy, and independent mobility among blind learners.

The reviewed articles demonstrate significant progress in the design of assistive technologies for individuals with visual impairments, particularly in the teaching and reinforcement of Braille literacy. Existing solutions range from tactile electronic devices capable of dynamically rendering Braille characters to educational tools integrating auditory feedback, mobile applications, and game-based learning strategies. Several projects have successfully employed low-cost platforms such as Arduino and mobile applications to enhance accessibility. In contrast, others have ventured into broader domains such as obstacle detection, mobility assistance, or color recognition. Collectively, these contributions highlight a rich ecosystem of initiatives aiming to foster inclusion and autonomy.

However, most of the surveyed devices exhibit notable limitations. Some rely heavily on complex mechanisms, such as servomotors to generate tactile relief, which increases cost and reduces durability. Others focus predominantly on complementary skills (e.g., mobility, music, or mathematics) rather than on Braille literacy itself. Moreover, while interactive prototypes exist, few explicitly integrate systematic teacher-led evaluation, meaning that most solutions prioritize individual practice but lack pedagogical feedback mechanisms. Another shortcoming lies in accessibility: specific proposals are either costly, difficult to reproduce in resource-limited educational settings, or remain at the conceptual or laboratory stage without evidence of large-scale deployment in schools.

The technological gap identified is the absence of a simple, durable, and low-cost device tailored explicitly for early Braille literacy that simultaneously supports teachers in monitoring and evaluating student progress. While previous works either emphasize tactile exploration or digital interactivity, they generally do not combine both dimensions in an integrated solution accessible to institutions with limited resources. The proposed Braille teaching keyboard addresses this gap by merging tactile learning through 3D-printed embossed keys with auditory reinforcement, complemented by a mobile application that enables teachers to design personalized tests and systematically evaluate student performance. This dual focus (student practice and teacher evaluation) represents a critical innovation that bridges existing shortcomings in the state of the art.

Together, these developments illustrate ongoing efforts to leverage low-cost electronics, tangible interfaces, and ICT tools to enhance both mobility and literacy among visually impaired learners, addressing persistent gaps in accessibility, pedagogy, and inclusion.

2.1 Comparative Analysis of Existing Solutions

Tab. 1 presents a comparative analysis of the solutions from literature review highlighting the improvements that the solution presented in this work introduce against the literature proposals.

Table 1 Comparative analysis of the existing solutions.

Work	Tactile Feedback	Audio	Teacher Evaluation	Cost	Reproducibility	Age Range
[2]	Yes	Yes	No	High	Low	Adults
[8]	Partial	Yes	Yes	Medium	Medium	8-12
[17]	Yes	Yes	No	Medium	Medium	4-6
Proposed Device	Yes	Yes	Yes	Low	High (3D printing + Arduino)	4-6

This comparison highlights that none of the reviewed devices simultaneously combine tactile exploration, audio reinforcement, low-cost manufacturing, and systematic teacher-guided evaluation. Our device fills this gap.

3 PROPOSAL

This section describes the stages in which the prototype "Braille alphabet trainer keyboard for blind children: An ICT-based solution" was developed. This solution was proposed as a support tool in learning the Braille alphabet, oriented to children who begin their primary education in the so-called Multiple Attention Centers (CAM) in Mazatlan Sinaloa, Mexico. The applied research developed in the thesis aimed to alleviate the lack of Braille language literacy due to the need for state-of-the-art didactic material to optimize the teaching-learning process. Next, the design and construction of the proposal are detailed through the stages of analysis, design, and construction. Stages are applied to the device and the mobile application (*app*).

3.1 Device Conceptual Design

The proposed device is designed to support early Braille literacy in children who are blind or severely visually impaired. It consists of a 3D-printed tactile keyboard in which each key embossed with a Braille character triggers audio playback of the corresponding letter through an integrated speaker with adjustable volume. A complementary Android application connects via Bluetooth, enabling teachers to design personalized evaluations aligned with individual learning needs.

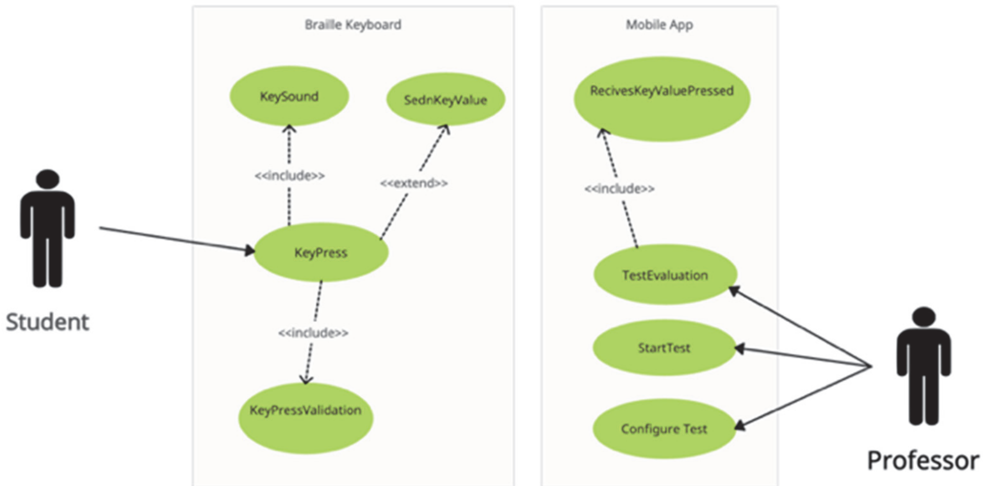

Figure 1 Braille device use case diagram

The device allows learners to explore tactile patterns freely and associate them with auditory cues, reinforcing perceptual discrimination prior to pressing each key and thereby supporting the development of foundational reading skills. Fig. 1 presents the system's use case diagram, illustrating the interaction between the student, the Braille keyboard, and the teacher through the mobile application. During evaluation, the teacher specifies the target sequence of letters, the student inputs responses on the keyboard, and the system transmits each keypress to both the app and the speaker. The application compares the input with the expected sequence and summarizes correct and incorrect attempts, providing the teacher with objective data to assess the student's progress in recognizing Braille patterns.

Subsequently, the needs presented in the described case were analysed, and the Software and Hardware requirements necessary for the prototype's operation were addressed. The software part refers mainly to functionalities implemented digitally through programming code that guides the operation of computer systems, such as mobile applications or instructions in a microcontroller where peripherals are connected.

Given the large number of buttons and the need for real-time interpretation, audio playback, and Bluetooth communication, the prototype was implemented on an Arduino Mega due to its greater processing and I/O capacity. The firmware, developed in C using the Arduino IDE, interfaces with a companion mobile application designed to support teachers by enabling efficient monitoring of student progress. The application connects to the device via Bluetooth to exchange practice and evaluation data.

The system provides two modes. Practice Mode allows learners to freely explore the keyboard and associate each tactile input with audio feedback, fostering familiarity with Braille patterns; teacher supervision is recommended to ensure conceptual understanding rather than positional memorization. Test Mode enables instructors to assign customized letter sequences and automatically assesses accuracy, response time, and error rates to derive a performance score. Together, the device and application provide a quantifiable sense of learner progress and streamline pedagogical evaluation.

Fig. 1 shows the Braille Device Use Case Diagram for the Keyboard and the Mobile Application. Regarding the Braille Keyboard, when the student presses a key, this one is validated. The system reproduces the key sound, and then the value of the pressed key is sent by Bluetooth to the mobile app. The professor can start a test and evaluate the pressed key.

3.2 Design and Construction of a Mobile Application for the Teacher

The next step involved the 3D printing of the casing, a task carried out using the Crealty V2 printer of the Ender brand. The choice of white PLA filament from the HATCHBOX brand ensured the desired aesthetics and durability. The total printing time for the housing components was 26 hours. The design was customized using the *Crealty Slicer* software and *Tinkercad* software, both of which played a significant role in shaping the final product. Fig. 2 captures the printer in action, producing a part of the prototype housing, with the components already printed in the distinctive white of the HATCHBOX PLA filament. The 3D printing process consumed a total of one and a half kilograms of filament.

The mobile application to support the teacher in using the electronic device for teaching Braille language was developed using *AppInventor* 2, an executable framework in the Web environment that facilitates the development of mobile applications. It is characterized using blocks that represent code statements and sentences, as well as the use of a graphical interface to design the screens. The app language is in Spanish for usability reasons. For the connection with a Bluetooth LE device, such as the HM-10 module, an add-on called Bluetooth LE was added, containing the necessary functionalities to communicate with the prototype. The user interface was then designed; at this point, it was determined that the necessary interfaces for the operation of the app were five: i) help interface, ii) interface for connection to a Bluetooth device, iii) test preparation interface, iv) test interface and v) results presentation interface. The functionality of each of these is detailed below.

1. Help interface. This provides the user with information on how to use the application and how to connect a keyboard to it via Bluetooth.
2. Interface of connection to a Bluetooth device. This screen (Fig. 2) shows the Bluetooth devices connected to the mobile device and in which the device corresponding to the Braille keyboard must be selected. When interacting with this screen for the first time, the user will be asked to turn on the mobile device's Bluetooth if it is not turned on. Once turned on, scanning of nearby devices can begin. The device being worked with has the name 5PBLE; once found, it is selected, and the "Connect" button is pressed. The status label will show "Connected" in green as soon as the Bluetooth device is connected, and the "Continue" button can be pressed. This button leads to the "Prepare Evaluation" screen.
3. Test preparation interface. Here, the number of letters the test will contain and which letters it will contain will be selected. Within this screen, it is possible to create a list of letters customized by the teacher. It works as follows: first, the letters are inserted one by one, they are written in the text box, and when the "Add to list" button is pressed, the list displayed at the bottom grows. The list of letters to be evaluated can be modified with the buttons "Delete selected", which deletes a selected letter in the list, or "Clear list," which allows deleting all records and starting a new list. The list allows the letters of the alphabet, the *ñ*, and accented vowels. Finally, once the list is defined, press the "Start Evaluation" button, which leads to the "Evaluation in progress" screen defined below.

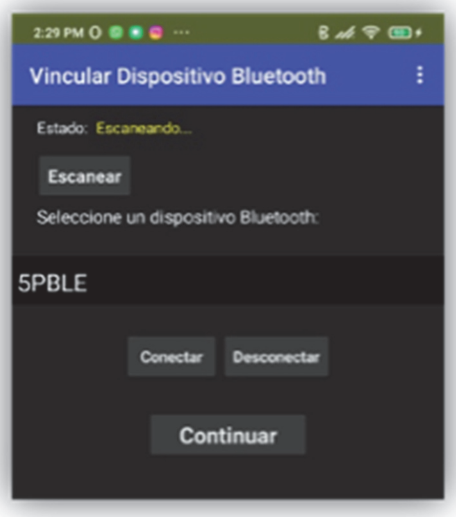

Figure 2 Bluetooth device pairing screen

4. Test interface. Fig. 3 shows the screen displayed while taking the test (test, evaluation of the blind student), showing preliminary results. The screen collects the student's hits and misses, and it is here that the student's proficiency in Braille is tested. The teacher gets a quick evaluation by showing which letters the student gets right and which are more complex. Once all the letters have been evaluated, the "View results"

button is pressed, which leads to the "Evaluation result" screen.

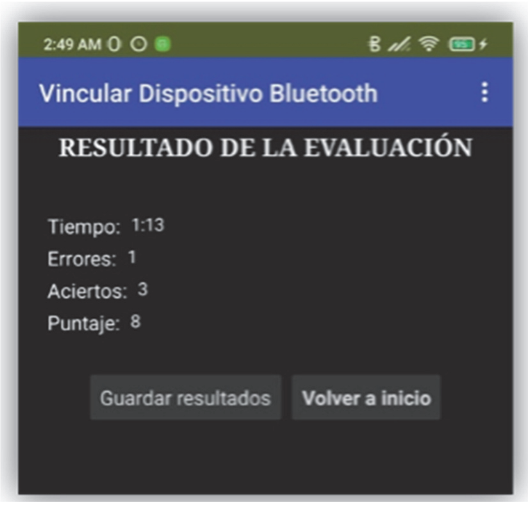

Figure 3 Evaluation in progress screen

5. Results interface. In this window of the mobile application (Fig. 4), the test results obtained by the child are shown. How many were he/she right, which ones were he/she wrong, etc. This screen shows the time the student took to complete the test, the number of errors, successes, and the average score for the latter. At the bottom of the screen are the options to save the test results and return them to the home page, the latter of which leads to the "Prepare Assessment" screen.

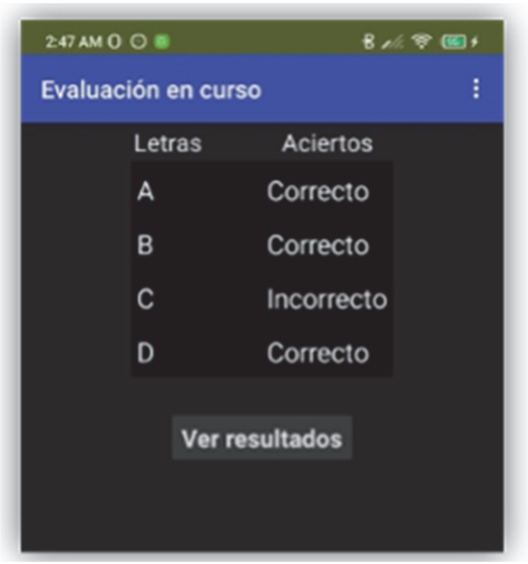

Figure 4 Evaluation result screen

3.3 Design of the Keyboard-Case

The prototype's design is a unique take on the traditional Pandora boxes used for arcade games. Measuring 40 by 25 centimeters and standing at approximately 7.5 centimeters, the box houses a circuit that powers the horn and connects all the buttons to an Arduino Mega. What sets this prototype apart is its use of tripal MDF (Medium Density Fibreboard) for the box, a material known for its durability and light weight.

The design of the button layout is shown in Fig. 5, which shows, among other things, the approximate dimensions of the box, the height of the keys, and their spacing. The order of these keys is read from left to right, starting from the top. It was determined that the distribution of the letters on the keyboard should be in alphabetical order because this is a popular method among teachers, being one of the most used in teaching the alphabet in written form. In addition, this teaching method is compatible with the Bliseo method. This method presents the first ten letters alphabetically and their variations in subsequent letters. However, the arrangement of the letters on the keyboard does not prevent the teacher from choosing another teaching method, such as the Alborada, Pérgamo, or Tomillo methods.

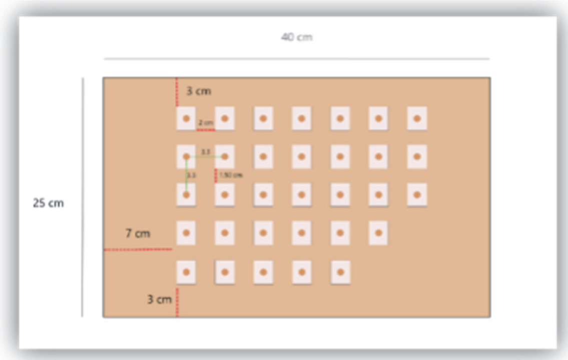

Figure 5 Key layout in the prototype

3.4 Integration

The electronic keyboard device for teaching Braille language was built from an MDF type wooden box, inside of which is the circuit of the buttons that protrude from a transparent acrylic cover. Fig. 6 shows the box containing the keyboard already assembled during the painting process with white and transparent lacquer to protect it from scratches.

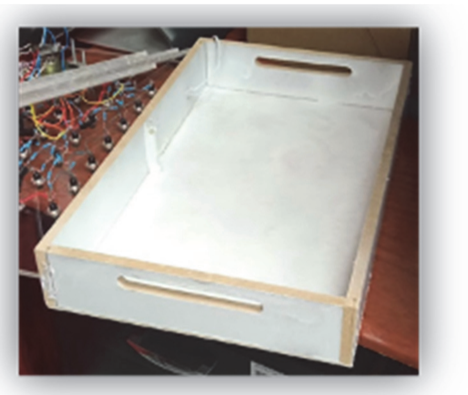

Figure 6 Electronic Braille keyboard container box

Subsequently, we proceeded with the design and printing of the keys. The Thingiverse repository was consulted, where a file with Braille's key design was entered. This was used as a basis, downloaded, and edited in the TinkerCAD software. In this modification, the size of the base of the key was considered for its assembly process, with the button used to construct the keyboard. Fig. 7 shows an example of the final key designed for this proposal.

Figure 7 Key designed for the keyboard and printed with the Crealty Ender V2 3D printer

The circuit (Fig. 8) that makes up the keyboard is designed so that each button receives a current that varies according to the letter pressed. An Arduino Mega microprocessor receives the current value through the analog pin A0, which interprets it and plays the sound of the letter pressed. This is done by implementing a DFPlayer Mini audio playback module, which has an SD (Secure Digital) memory card that stores all the audio in MP3 (MPEG-2 Audio Layer III) format required for the project. As shown in Fig. 9, this module communicates with the Arduino motherboard through a serial communication created with pins 10 and 11, which are connected to the respective *Tx* and *Rx* ports of the DF Player Mini device.

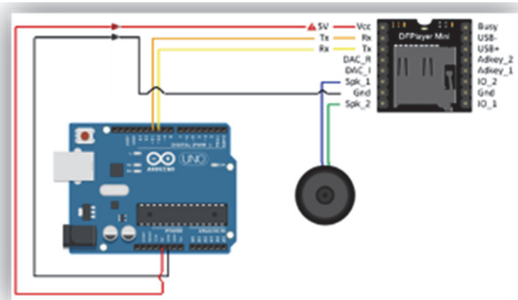

Figure 8 Connecting the DF Player mini module to Arduino

Figure 9 Finished prototype

In Practice Mode, the prototype processes the signal received through the Arduino's analog pin A0, triggering both audio playback and data transmission to a mobile device via an HM-10 Bluetooth module. The system sends a character-coded text corresponding to the pressed key through a serial connection established between Arduino pins 12-13 and the HM-10 TXD/RXD ports, with the module powered at 3.3 V. The keypad's electronic design assigns a distinct voltage level to A0 for each button using series resistors of different values, enabling accurate key identification. The components were subsequently integrated into the final Braille-teaching keyboard, as shown in Fig. 9.

4 EXPERIMENTAL EVALUATIONS

To assess the effectiveness of the proposed Braille teaching keyboard and its mobile application, an experimental evaluation was conducted with visually impaired participants from two contexts: a blind child enrolled at CAM No. 50, and two visually impaired adults employed at the *Universidad Autónoma de Sinaloa*, working in the *Programa de Atención a la Diversidad* (AdiUAS). A Braille-specialized teacher facilitated all sessions.

4.1 Participants

A total of three visually impaired participants and one braille instructor took part in the study (Tab. 2).

All participants completed informed consent (or parental consent) procedures according to institutional guidelines. The sample size is consistent with exploratory usability studies in accessibility research.

Table 2 List of participants in the braille keyboard experiment

Participant	Age	Condition	Affiliation	Braille experience
P1	5	Congenital blindness	CAM No. 50	Beginner
P2	29	Blind	ADIUAS, UAS	Intermediate
P3	34	Blind	ADIUAS, UAS	Advanced

4.2 Experimental Design

The study followed a within-subjects design:

- Each participant performed the same Braille character identification task using two methods:
    - Traditional method: tactile laminated Braille sheets.
    - Proposed device: 3D-printed electronic Braille keyboard.
- Each participant completed two sessions on different days to reduce learning bias.

Each participant was asked to identify 10 letters spoken aloud by the teacher (randomized per session).

The metrics proposed are:

- Correctness (%) - proportion of correctly identified letters.
- Mean Time per Letter (seconds).
- Number of Attempts per Letter.
- Teacher Usability Score (SUS 0-100) for the mobile app and evaluation process.

4.3 Procedure

- Familiarization (10 min): Participants explored both systems.
- Task Execution: For each letter, participants attempted identification.
- Data Logging:

- Traditional method: teacher manually recorded performance.
- Proposed system: keyboard + app automatically recorded input and timing.

- Post-Session Feedback: The teacher completed a usability questionnaire for the device and app.

The full study lasted approximately 45 minutes per participant.

4.4 Results

The correctness is shown in Tab. 3, this is the accuracy when participants are using the proposed device.

Table 3 Results for correctness

Participant	Traditional / %	Proposed Device / %
P1 (child)	40	80
P2 (adult)	70	90
P3 (adult)	90	100
Mean	66,7	90,0

Participants achieved 23.3% higher accuracy when using the proposed device.

With regard to time per Letter (seconds), the faster cognitive recognition using tactile plus auditive reinforcement (Tab. 4) was evaluated.

Table 4 Results for time per letter pushed

Participant	Traditional / %	Proposed Device / %
P1	9,2	6,1
P2	6,5	4,0
P3	5,2	3,8
Mean	6,97	4,63

The proposed system reduced identification time by 33.6%, indicating faster cognitive recognition through tactile + auditory reinforcement.

The evaluation for the letter identification (Attempts per Letter), results are detailed in Tab. 5.

Table 5 Results for time per certainty in letter identification

Participant	Traditional / %	Proposed Device / %
P1	2,4	1,5
P2	1,8	1,2
P3	1,3	1,0
Mean	1,83	1,23

Participants required 32.8% fewer attempts, demonstrating improved certainty in letter identification.

For the evaluation for the Teacher Usability Score (SUS), the Braille instructor rated the system as:

- SUS = 84,5/100, categorized as Excellent usability.
- Positive comments included:
  - "Real-time automatic logging reduces teacher workload."
  - "Children respond better to tactile plus auditory feedback."
  - "The evaluation module is extremely useful for tracking progress."
  - "ADIUAS can produce these devices for teaching Braille in UAS."

4.5 Statistical Analysis

Given the small sample size, the Wilcoxon signed-rank test was applied (Tab. 6).

Table 6 Results for Wilcoxon signed-rank test

Metric	p-value	Interpretation
Correctness	0,043	Significant improvement
Time per letter	0,042	Significant improvement
Attempts	0,041	Significant improvement

At α = 0,05, results indicate statistically significant performance gains using the proposed device.

4.6 Discussion

The evaluation indicates that the proposed Braille teaching keyboard enhances letter-identification accuracy, reduces task completion time, and increases learner confidence, benefiting both novice and advanced readers. The system also provides teachers with immediate and reliable performance data, facilitating individualized instruction, and demonstrates high usability and ease of integration in real educational settings. These results support the hypothesis that combining 3D-printed tactile keys, auditory feedback, and digital evaluation yields measurable improvements over traditional Braille teaching methods. On the other hand, several limitations should be considered when interpreting these findings. The sample size was small, as is common in accessibility research, requiring replication with larger and more diverse populations. The study assessed only short-term learning outcomes, leaving longitudinal effects on skill development and retention unexplored. Additionally, prototype durability was not evaluated under prolonged classroom use, limiting conclusions about long-term operational reliability. Future work will address these limitations through multi-site longitudinal studies and hardware enhancements - particularly PCB integration - to improve system robustness and support broader deployment.

5 CONCLUSIONS

This study addressed the persistent barriers faced by learners with visual impairment by proposing a low-cost, multisensory system designed to strengthen early Braille literacy. The research presented the conceptualization, development, and evaluation of an electronic Braille teaching device integrating 3D-printed tactile keys, auditory reinforcement, and a companion mobile application for real-time pedagogical monitoring. Together, these components support foundational perceptual skills, promote user confidence, and reduce instructional burden through automated assessment and individualized practice.

The experimental deployment in CAM No. 50 and AdiUAS demonstrated significant improvements in accuracy, task completion time, and user experience compared to traditional tactile sheets. The excellent usability rating provided by the Braille instructor underscores the pedagogical relevance of real-time feedback mechanisms - an aspect largely overlooked in existing solutions. The contributions of this work include: (i) a systematic review that identifies technological and pedagogical gaps in current Braille-teaching devices; (ii) the design and implementation of a functional prototype currently operating in a real educational context; (iii) the development and copyright registration of the companion software, aligned with national priorities in inclusive education; and (iv) a direct social impact through the donation and adoption of the system in a center serving blind children in southern Sinaloa.

Future work will focus on enhancing hardware robustness through PCB integration, expanding instructional capabilities toward syllables and words, and conducting longitudinal studies with larger cohorts to assess learning retention and broader pedagogical effects. These efforts aim to consolidate the proposed system as a scalable and effective solution for promoting equitable Braille literacy in low-resource educational environments.

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