TacNote: Tactile and Audio Note-Taking for Non-Visual Access

Wan-Chen Lee
National Taiwan University
Taipei, Taiwan
wanchen30@gmail.com

Ching-Wen Hung
National Taiwan University
Taipei, Taiwan
amie12349@cmlab.csie.ntu.edu.tw

Chao-Hsien Ting
National Taiwan University
Taipei, Taiwan
chaohsien1222@gmail.com

Peggy Chi
National Taiwan University
Taipei, Taiwan
peggychi@ntu.edu.tw

Bing-Yu Chen
National Taiwan University
Taipei, Taiwan
robin@ntu.edu.tw

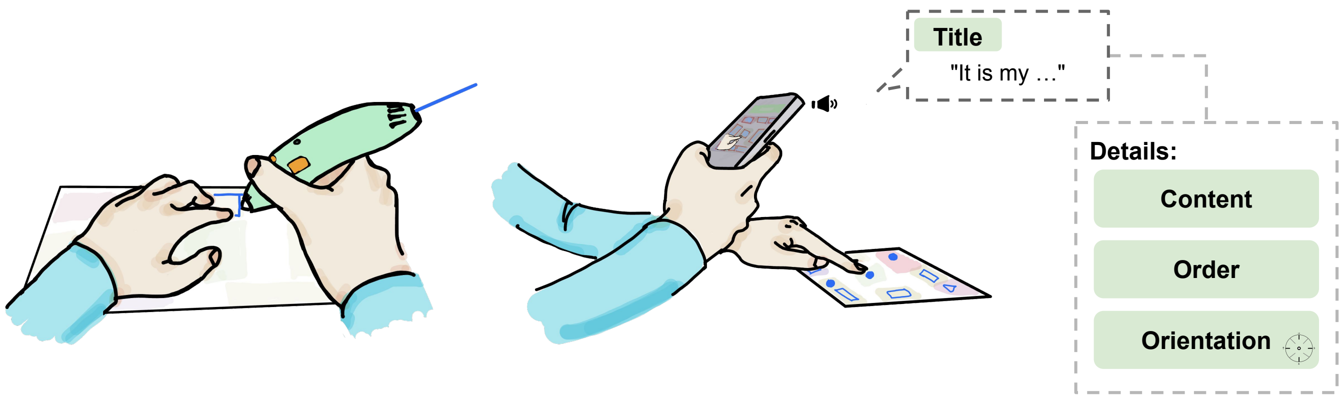

Figure 1: Using TacNote, BVI users can create tactile graphics and annotate everyday objects through our mobile app. First, users create tactile graphics free-hand with a 3D printing pen. Next, they scan and annotate the created graphics by using our camera-based app. Users can interact with physical labels via finger-pointing and navigate the hierarchical information in the reading mode, which provides more details such as content, order, and relative orientation, all with audio feedback.

ABSTRACT

Blind and visually impaired (BVI) people primarily rely on non-visual senses to interact with a physical environment. Doing so requires a high cognitive load to perceive and memorize the presence of a large set of objects, such as at home or in a learning setting. In this work, we explored opportunities to enable object-centric note-taking by using a 3D printing pen for interactive, personalized tactile annotations. We first identified the benefits and challenges of self-created tactile graphics in a formative diary study. Then, we developed TacNote, a system that enables BVI users to annotate, explore, and memorize critical information associated with everyday objects. Using TacNote, the users create tactile graphics with a 3D printing pen and attach them to the target objects. They capture and organize the physical labels by using TacNote's camera-based mobile app. In addition, they can specify locations, ordering, and hierarchy via finger-pointing interaction and receive audio feedback. Our user study with ten BVI participants showed that TacNote effectively alleviated the memory burden, offering a promising solution for enhancing users' access to information.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; **Accessibility technologies**.

KEYWORDS

Accessibility, Tactile graphics, 3D printing pen, Assistive technology, Mobile Application, Fabrication

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1 INTRODUCTION

Visual sense is a primary perception for people with normal vision to quickly process complex information simultaneously [3, 12].

However, BVI people must extensively rely on nonvisual senses, such as verbal descriptions and tactile characteristics, to comprehend the appearance, content, and spatial relationships of physical objects in an environment [8]. This reliance on nonvisual cues may be particularly challenging to BVI people when the diversity of objects or non-fixed positions increases because of relatively higher cognitive demands, impacting the overall cognitive functioning [14, 40, 53].

Prior studies have suggested that BVI people exhibit superior tactile abilities relative to their sighted counterparts [52]. They use sequential memory and continuous tactile strategies to compensate for the lack of visual information [29, 39, 53]. However, they may encounter significant cognitive burdens in navigating daily activities, from item organization to abstract concept understanding. Therefore, BVI people utilize a variety of tools (e.g., rubber bands, stickers, and Braille) to create diverse tactile graphics and augment them to everyday items. These objects facilitate efficient identification and comprehension of information encountered through touch. Studies have found that a high cognitive load and memorization are required to identify such physical annotations from a long period or tactile nuances [11, 53].

To support BVI users, researchers have proposed computer vision-based solutions to enable real-time access to real-world information through mobile cameras [6, 58, 59]. Recent studies have used 3D printing technology to produce tactile graphics with greater variability for learning and recognition tasks [23]. For example, Pandey et al. combined tactile graphics with audio instructions to enhance a drawing process [38]. Wang et al. combined 3D printing objects with voice broadcasts to provide spatial information in art museums [54]. Laser-cutting technology can also be used to create tactile graphics with audio feedback [49]. Users can further define the content by operating tactile graphics on paper with voice input [48]. Finally, with the support from sighted people on pre-made tactile graphics and digital markings, several researchers have shown that BVI people increase their exploration [43, 56]. While these designs offer BVI people greater access to information and exploration options, they often require assistance from sighted people on tactile graphic creation.

The advancement of 3D printing pens has enabled DIY communities to create three-dimensional objects with free-hand interactions [47]. Certain models have a low-temperature heated tip, making them safe for children and average users [19]. This introduces opportunities for BVI people to produce tactile graphics independently and safely. Given that there is limited research on the use of such tools in the BVI community, we first conducted an exploratory 15-day diary study with five BVI people to understand how they would use a 3D printing pen and identify their questions on and needs related to tactile graphics.

We then designed TacNote, an interactive system for BVI people to create tactile graphics with descriptive audio annotations via a mobile app, which enables non-visual access to physical objects. Users can use our mobile app to scan the tactile graphics that they created and annotate or edit the content of the tactile marks associated with objects. They can interact with the tactile graphics in real-time by using their fingertips to explore the location, order, and hierarchy of the annotated content with audio feedback from our app. To evaluate the usability and feasibility of TacNote, we conducted a user study with ten BVI people. Through tasks and semi-structured interviews, we confirmed the feasibility of TacNote, received feedback, and provided recommendations for future design directions. In summary, we make the following contributions:

- A formative study that investigated practices and challenges for BVI people with respect to the use of a 3D printing pen.
- An interactive system that enables BVI users to create tactile graphics, add audio annotations, and access audio feedback for interacting with physical objects.
- A user study with ten BVI users that demonstrated the benefits and opportunities of tactile and audio note-taking.

2 RELATED WORK

Our work was based on prior art on the existing practices of how BVI people identify objects and the support of tactile graphic creation. We drew inspiration from accessible design principles, creative tools, and methods.

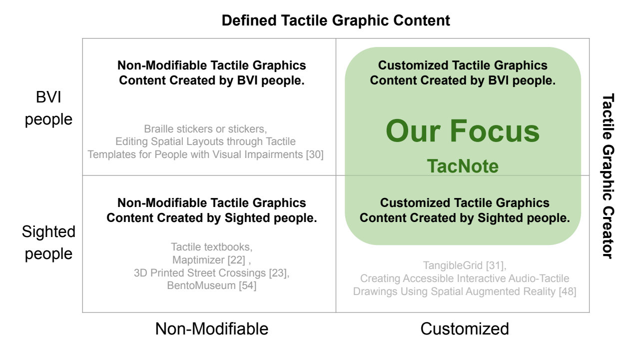

Figure 2: TacNote focus: The rows indicate whether BVI or sighted people create the tactile graphics, and the columns indicate whether the content is customized. TacNote's main focus is to support BVI people in creating and defining their own customized tactile graphics while offering the capability to co-work with sighted people.

2.1 Tactile-Based Assistance

BVI people use various tools to incorporate tactile graphics onto objects, such as rubber bands, stickers, and braille labels, to differentiate between items or comprehend graphical information. While rubber bands and stickers are low-cost and readily available, they are limited to graphic variability. In contrast, systematic approaches such as Braille slates and styluses and Braille labelers can create tactile Braille labels [34], but they require proficiency through learning. Toussaint and Tiger explained, "According to the National Braille Press only 12% of legally blind people can read Braille (...)" [50]. Goudiras et al. reported that people who developed visual impairment as younger adults or later in life tend to favor screen readers or audio-recorded materials and therefore, are less likely to opt for Braille training [15].

Previous research has utilized 3D printing technology to create 3D tactile graphics for visually impaired children's education [28] and orientation training (including street [23] and map recognition [22]). Guo et al. investigated the creation of 3D printing interfaces via mobile devices and collaborative processes [17]. However, these methods are restricted to specific scenarios. There remains a challenge to allow BVI people to personalize and swiftly generate tactile graphics independently.

2.2 Audio-Based Assistance

Assistive technologies with voice input and audio feedback are increasingly available on desktop and mobile devices. By using screen readers, crowd-supported apps (e.g., "Be My Eyes" [20]), and computer vision techniques [6, 58, 59], BVI users can receive real-time or remote assistance with auditory descriptions, and further interact with real-world interfaces such as a control panel [16, 18]. However, the absence of tactile feedback can result in a memory burden for BVI people when repeatedly listening and processing the auditory content.

2.3 Tactile and Audio Assistance

Pandey et al. [38] found that combining tactile graphics with audio cues as a more effective design for BVI people. Similar approaches utilizing these elements have been employed for various purposes. In this section, we classify the existing literature on tactile and audio assistance into non-autonomous creation and autonomous creation. Additionally, we explore the advancements in 3D fabrication.

2.3.1 ***Non-Autonomous Creation:*** Examples include using capacitive technology and 3D printing for map exploration [24], overlaying 3D printing onto mobile device designs to assist with mobile phone operation [57], and teaching circuits [10, 13] and electronic diagrams [21]. Additionally, this design approach can be applied to spatial understanding scenarios, such as experience design for layered floor plans in a museum [54]. There are also methods to combine with a camera, such as teaching designs that combine hand recognition [43] or physical data visualizations [35], table game designs [49] with augmented reality technology, and teaching aids for custom content editing through voice commands [48]. These design methods provide BVI people versatile interaction experiences for better understanding. However, most of these tactile artifacts are limited to specific applications and can rarely be created by BVI people themselves. They are mostly designed and produced by sighted people prior to the interaction phase with BVI people.

2.3.2 ***Autonomous Creation:*** There has been extensive research on tools that enable BVI people to independently create tactile graphics and overcome authoring challenges. For instance, Li et al. utilized capsule paper and a mobile device with audio functionality [30], whereas Li et al. [31] developed a device involving tangible brackets on a baseboard. Both approaches aimed to empower visually impaired individuals in creating website layouts for website design. Interactive tools with tactile feedback can assist BVI people in creating images or drawings by using either a pin-matrix display [7] or a 2.5D tactile shape display [46]. Savage et al. [42] utilized a 3D printer to print raised lines of filament, creating large tactile displays that enable BVI individuals to understand maps and interact with them. Although these designs are user-friendly and provide opportunities for self-directed creation and exploration, their scope of application is relatively specific. To offer BVI people more autonomy and interaction in their creation process, we explored the alternatives among the existing creative tools.

ID	Gender	Age	Occupation	Vision Level
B1	Man	23	Legal Specialist	Blind, later on
B2	Woman	22	Student	Blind, later on
B3	Woman	52	Music teacher	Seriously low vision
B4	Man	45	Braille proofreader	Blind, later on
B5	Woman	19	Student	Blind, since birth

Table 1: Participant demographic of our formative study.

2.3.3 ***3D Fabrication:*** 3D printing is a popular and effective method for a high degree-of-freedom design. However, it can be difficult for BVI people to design and generate independently. As an alternative, we prioritized the use of 3D printing pens, which are similar to 3D printing in terms of high mobility and lower learning costs. A majority of prior research on 3D printing pens has focused on sighted people, such as to create small tools [41] or accelerate the generation of 3D models [47]. A few studies have observed how BVI people used 3D printing pens for drawing [55]. There has been little research on the interaction design of 3D printing pens for BVI people. To enable BVI users to create and design for various needs, it is critical to fully understand the benefits and challenges by using a 3D pen with assistive technologies.

We drew inspiration from these methods to combine 3D printing pens and mobile assistive technologies, aiming to support BVI people in creating custom symbols and content that they can review and modify independently.

3 FORMATIVE STUDY

We conducted a formative study with five BVI participants using a 3D printing pen. This study involved a tutorial, a 15-day diary, and a semi-structured interview to explore their daily usage and potential challenges.

3.1 Participants

We sent invitations through authors' connections and public recruitment posts on social media. We recruited five BVI people (two men and three women), aged between 19 and 52 years old (mean=32.2). Four of them were fully blind, while one had a severe low vision. Of the four blind people, one was blind since birth, while the others lost their vision later in life (see Table 1). None of them had prior experience of using a 3D printing pen. We carefully selected individuals with diverse professions and interests. This was to better understand the various ways in which 3D printing pens could be utilized by BVI people of different backgrounds. We refer to our BVI participants as B1-B5 in the following sections.

3.2 Material

We provided each participant with a toolkit consisting of a 3D printing pen, 144 plastic filaments, 30 PVC plastic sheets, and a charger (see Figure 3). The 3D printing pen used in this study was 3Doodler Start+ by WobbleWorks [1], which offers a low-heat tip and is wireless. These features make it suitable for BVI people to draw and create while touching it without the concern of burning issues or being restricted by location. Due to the low-temperature

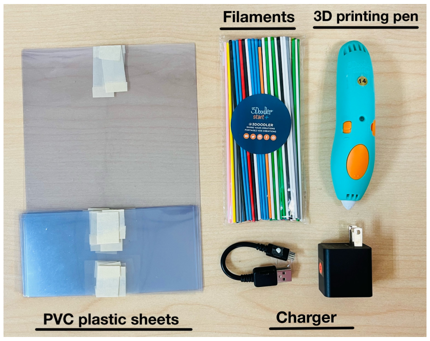

Figure 3: Toolkit provided in our formative study, including a 3D printing pen with its compatible filaments and a charger, and PVC plastic sheets for object attachment.

nature of this 3D printing pen, it can easily detach from most materials, which may not be ideal for BVI people to repeatedly explore and draw. Therefore, we selected PVC plastic sheets that securely adhere to the 3D printing pen, allowing BVI people to explore and draw as desired without detachment concerns.

3.3 Procedure

To better understand where BVI people would like to apply 3D printing pens in their daily lives, we referred to previous studies and recorded the users' design process through a diary log [26, 27, 44]. We designed a study that included a tutorial, a 15-day diary study, and semi-structured interviews. Our study began with a semi-structured introduction session to assess the participants' prior knowledge of tactile graphics and their familiarity with a 3D printing pen. Through the tutorial, we instructed the participants on the basic usage of the 3D pen without 2D graphics or predefined drawings and encouraged them to explore and use a 3D printing pen effectively for the subsequent 15-day diary study.

In our 15-day study, the participants conducted prompted and unprompted activities (see Table 2) using the 3D printing pen in familiar settings, such as their homes and schools. The initial five-day period was designated for unprompted activities, wherein the participants were free to select any design subject and conceptualize ideas. Next, the latter five-day period (Day 6 to 10) was designated as prompted activities. We provided five prompts on the organization and categorization of similar items, guidance, additional functions with technology, learning and teaching, and gaming and entertainment. The participants received the five prompts on Day 6 and were required to create and record their works the basis of on the provided prompts for the remainder of the five-day period. In the final five days, the participants resumed the unprompted activities of the initial period, enabling them to freely generate and record their creative ideas.

During this 15-day period, the participants were asked to produce at least one artwork by their 3D printing pen per day, with no upper limit imposed. The participants were required to record their creative motivation, location, and problem-solving strategies and transmit this information to the researchers via social media or email. Consistent reminders were issued to participants the throughout the 15-day study period to ensure the timely completion of the task and adequate responses to any inquiries or feedback related to their artistic output.

TimeLine	Prompt Type
Tutorial	-
Day01-Day05	Unprompted
Day06-Day10	prompted (5 probe questions)
Day11-Day15	Unprompted
Semi-structured interviews	-

Table 2: Timeline of 15-day formative study, including a tutorial, prompted and unprompted activities, and interviews.

Finally, we conducted semi-structured interviews with each participant after their 15-day diary study. These interviews allowed us to gain deeper insights into their creative process, potential applications, and the issues that they sought to address using the 3D printing pen.

3.4 Findings

Our formative study yielded three primary findings based on the participants' feedback, including an evaluation of the advantages of the 3D printing pen, an analysis of the common scenarios based on the submitted works, and recommendations for enhancing the current technology of the 3D pen.

3.4.1 ***Benefits of a 3D printing pen.*** During the interview process, the participants noted that the absence of tactile graphics when attempting to comprehend two-dimensional objects places an extra burden on their effort and memory. Because of the high complexity of these objects, they often give up on understanding and learning. However, with the aid of a 3D printing pen, abstract graphics or symbols could be quickly transformed into 3D models, simplifying intricate content and facilitating comprehension. This allowed them to comprehend areas that they might not typically encounter, such as mathematics or complex rule-based card games.

Moreover, the participants noted that a 3D printing pen was a more efficient tool for creating tactile graphics than other methods (hot-melt pens, Braille stickers, rubber bands, etc.). B1 mentioned that "*it is faster and more convenient, with a more accurate output, achieving a completion rate of at least 70 percent.*" B2 pointed out that "*a 3D printing pen can easily depict symbols that are difficult to describe with words.*" B4 stated that "*3D printing pens are more flexible and convenient than Braille printers, which were large, expensive.*" B4 also noted that "*no matter how the text looks like, it can be recognized as long as it's written by oneself.*" Additionally, B5 noted that "*symbols produced using 3D printing pens are waterproof, and the tool is easy to carry.*" Overall, all five participants expressed positive feedback on the 3D printing pen, highlighting its ability to rapidly create tactile graphics, portability, and accessibility.

3.4.2 ***Common applications of a 3D printing pen.*** During the 15-day diary study, we collected a total of 69 works from the five participants. We identified four categories: (1) *similar item discrimination*, (2) *cmprehension of graphics*, (3) *planar characters transformed into 3D*, and (4) others (see Figure 4).

The "**Similar Item Discrimination**" category aimed to enhance the participants' ability to recognize objects that are difficult to identify on the basis of appearance alone. Among the 69 submissions,

Figure 4: Collection of works from the participant's 15-days test. Divided into four categories and others, from top to bottom: Similar Item Discrimination, Comprehension of Graphics, Planar Characters Transformed into 3D, and Others.

27 were related to the discrimination of similar items, including toiletries, medication, remote control buttons, switches, and paper documents. All five participants mentioned this category, and every submission included at least three related items, indicating that it is a prevalent application scenario. B2 pointed out that "*while some systems can recognize the text on a bottle or package, there are instances where they do not want to listen to a lot of information and just want to know what the item is.*" B3 said that "*because everyone categorizes items differently, not everyone will use containers with different shapes to classify them, making 3D printing pens a suitable tool for labeling and categorizing according to personal preferences.*" The participants emphasized the need for quick identification and personalized categorization, which 3D printing pens could facilitate.

The "**Comprehension of Graphics**" category includes 18 of 69 works that are specifically designed to aid in educational settings and promote spatial understanding. These works consist of various graphical representations such as charts, line graphs, mathematical symbols, fonts, and other visual aids that facilitate the recognition of symbols and abstract concepts. The category also includes individual drawing exercises. Interestingly, three out of five participants emphasized the importance of spatial understanding, particularly for directional training and constructing mental maps to help BVI people understand spatial configurations more effectively. For instance, B1 stressed "*the need for sighted people to create maps of unfamiliar surroundings to provide BVI people with a preliminary understanding before exploring.*" B2 suggested that "*a 3D printing pen could be an excellent tool for quickly creating drawings.*" Moreover, B3 pointed out that "*BVI people have a keen interest in knowing the spatial location of buildings and require simplified maps of transportation routes.*" The category's focus on comprehending graphics highlights the importance of visual aids in enhancing educational experiences and improving spatial understanding for individuals with different abilities.

The "**Planar Characters Transformed into 3D**" category consisted of 16 works that added meaningful symbolic content to surfaces that are traditionally difficult for BVI people to understand and use, such as scales on microwaves, button functions on washing machines, expiration dates on packaging, and numerals on game cards. By incorporating 3D touch, these works provided more information and convenience for BVI people, enabling them to better integrate into society.

Finally, some works could not be classified into the aforementioned four categories, such as handicrafts (e.g., rings and hooks) or measuring banknotes.

3.4.3 ***Desired feature enhancements.*** After conducting semi-structured interviews, we found that the participants encountered some unresolved issues while using the 3D printing pen to solve contextual problems. B1 mentioned "*the need for a recording system that could edit and define forgotten markings,*" while B2 reported "*desired meaningful markings that were less likely to be forgotten and required a legend for numerous or complex objects.*" B3 pointed out "*the 3D printing pen's limitations in recording too much content due to the volume of the object,*" and B4 noted that "*the usage frequency and order of medication could be challenging to remember.*" The participants wanted to further define and edit the symbols' content rather than merely marking them. In addition, B2 and B5 hoped for an audio prompt for battery and pen status changes, while B1 and B3 mentioned that "*some materials might cause difficulty in adhering to the 3D printing material.*"

Overall, the participants gave positive feedback on the use of the 3D printing pen and expressed a desire to add more assistive features to the tactile graphics that they created. They hoped that the system would offer more comprehensive labeling and recording capabilities, reducing the burden of these activities in their current contexts. Consequently, we identified the necessary features and design space and proposed TacNote.

4 TACNOTE

TacNote is a fully customizable tactile note-taking and interactive mobile system specially designed for BVI people. It consists of two main components: (1) a mobile web application with an accessible front-end design for screen reader access, and (2) a 3D printing pen for creating physical tactile graphics. Figure 5 shows the user workflow using TacNote.

4.1 Mobile web application

TacNote offers a mobile web app to scan and interact with the tactile graphics. Our front-end interface design prioritizes simplicity for accessibility and ease of use for BVI people. Users interact with TacNote by using two modes: the "Create Note" and the "Read Note" modes (see Figure 5 top and bottom, respectively). Our user flow includes four primary functions: (i) *Capturing images*, where users can take by photos using the rear camera, and the backend processes the image to extract the location of tactile graphics: (ii) *Selecting symbols*, where users can choose physical tactile symbols via the rear camera with real-time sound feedback and selection when the index finger overlaps with a symbol: (iii) *Inputting custom data*, where users can record hierarchy information, order numbers, and choose whether to generate relative positions between symbols by using voice or text input; and (iv) *Reading custom data*, where the system divides the hierarchy data into two parts for display: the top layer data (as title) are played and displayed via voice when the user selects the symbol, and the secondary data (as content),

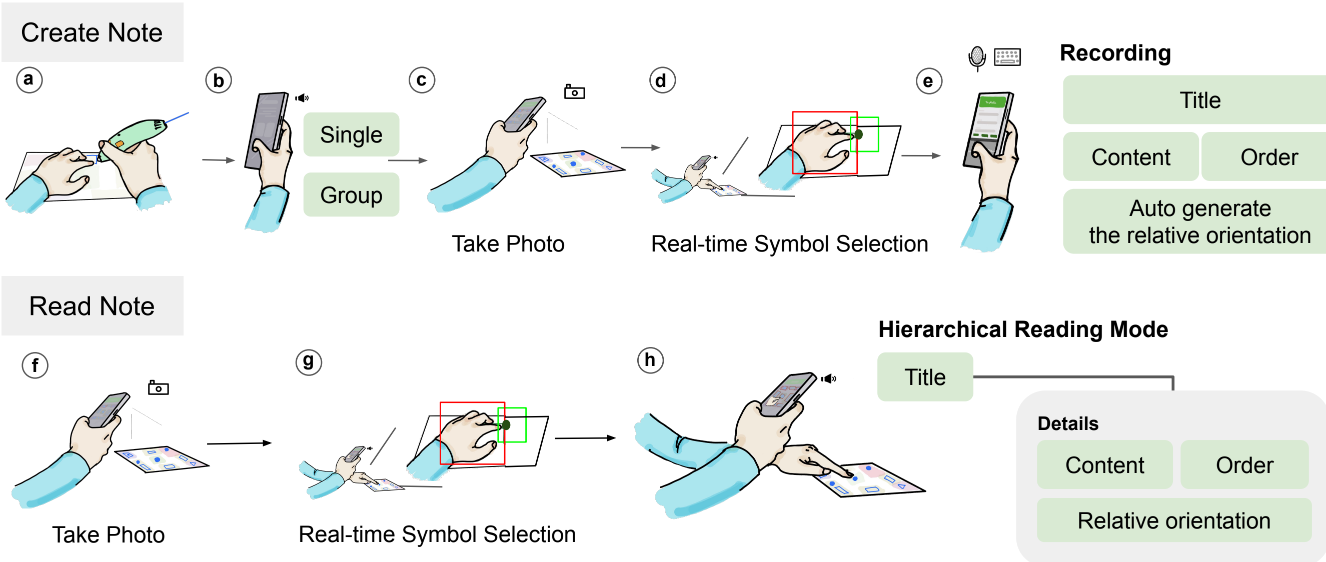

Figure 5: TacNote pipeline. (1) Create Note: The users use a 3D printing pen to draw tactile graphics, choose a recording mode (group/single), take a picture of the note, and select symbols with their fingers. Then, they can record the note's information by using either text or voice input (a-e). (2) Read Note: The users take a picture of the note that they want to explore and select symbols with their fingers. During the selection process, they can access the first layer of information and then select details to understand the second layer of information (content, order, and relative orientation). The users can also edit their note as needed (f-h).

sequence, and automatically generated relative positions between symbols can be read by the user after confirmation.

TacNote's mobile app offers three major functionalities, namely image processing and finger detection, recording methods, and filtering mechanisms:

4.1.1 ***Image processing and finger detection.*** TacNote was developed using Python 3.8 as the primary development environment and OpenCV as the primary image-processing library. This combination was used to capture the symbols present in user-captured images and detect similar notes in real-time. Additionally, the Google MediaPipe Hands API was utilized to perform hand detection and capture the real-time position of the index finger. Detailed explanations of each function implementation are provided below.

Capture symbols: To accurately recognize a wide range of shapes, including abstract patterns, text, and numbers, our system utilized color extraction and connectivity calculation to identify tactile graphics in an image. Our primary focus was on blue 3D printing pen filaments. The system used OpenCV to extract the boundary values of the blue color, particularly the BGR values ranging from 101 to 242 for blue, 73 to 160 for green, and 12 to 91 for red. Morphological transformations [36], such as closing and dilation, were then applied to the resulting image. The system computed the connected components of the labels in the image [37] and established a minimum coverage area of 3000 for a label to be regarded as a symbol (as Figure 6). It filtered the residual material that was not the same size as the main lines of the notes. The position of each symbol was stored in our database, enabling direct querying and saving computational resources. This approach significantly improved the overall efficiency when searching for similar notes.

Real-time similar notes detection: To enable users to capture the same note content in different spatial environments, we used the scale-invariant feature transform (SIFT) [32, 33] algorithm for feature matching. Firstly, we performed feature point computation on the photo taken by the user during the "Create Note" process. In the "Symbol Selection" process, feature point computation on each frame of the live image received in real-time (returning one frame every 1.3 seconds). When the number of matched feature points between the two exceeded the set threshold, it was displayed as a similar note captured in the real-time image. Additionally, the "Read Note-Find Note" feature also employed the SIFT algorithm for feature matching between user-captured notes and the database. This approach enabled the system to precisely identify matching notes based on the extracted feature points.

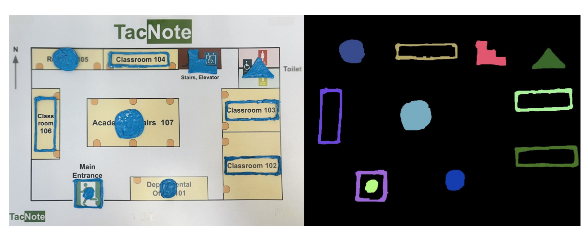

Figure 6: Symbols extracted after image processing. Left: Original image taken by the user. Right: Symbols detected after color extraction and morphological transformations.

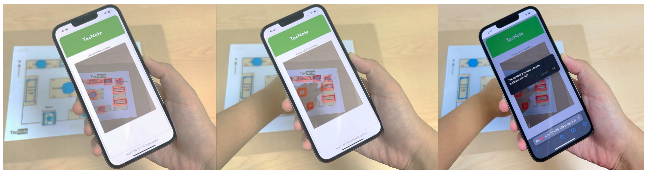

Figure 7: The user selects a symbol on TacNote. Left: Similar graphics are detected in real-time, and the corresponding symbol is displayed. Middle: Users can interact with the symbol using their fingers. Right: TacNote immediately provides relevant first-layer information after the interaction. The process includes audio feedback.

Finger detection: We utilized the Google MediaPipe Hands API [51] as a tool for real-time hand detection and extracted the position of the user's index fingertip (8.INDEX_FINGER_TIP). By combining this with the previously detected locations of notes and symbols in real-time images, the users could trigger a voice interaction by touching the tactile symbols with their index fingertip (Figure 7). We also used various sound effects to provide clear feedback to users on the detection of hands, notes, and touch events in the current camera view.

4.1.2 ***Recording methods****.* To optimize the note-taking efficiency and clarity, we analyzed the most commonly used record elements in our formative study, including name, purpose, order, and orientation. On the basis of this analysis, we developed a hierarchical reading mode to address the issue of lengthy content that the participants expressed a desire to avoid. When creating a note, the users could input information such as title (name), content, order, and whether to generate relative orientation symbols through text or voice input. Only the title was required. The other information was optional, based on the user's needs. When reading a note, we presented the information in a hierarchical manner. At the "Symbol Selection" stage, the users could touch the haptic symbol to listen to the first layer of information, which was the title. After confirming their selection, the users could then access the detailed information on content, order, and relative orientation. This design facilitated easier reading and management of notes, avoided lengthy content, and made the record elements clearer and more understandable.

To calculate the symbols' relative orientation for generation, we used the previously extracted locations of symbols from the notes. The user selected a symbol as the central point, and we calculated the relative positions of the other symbols from that point with eight directions labeled using the clock method, which is a familiar method for BVI users. The eight directions were arranged in clockwise order (Figure 8). We adopted this method to make the method more user-friendly for BVI people.

4.1.3 ***Filtering mechanisms****.* We implemented a specialized mechanism within TacNote to streamline the user experience. This included a photo quality filter and verification process to ensure the presence of tactile symbols within the captured images. If the system detected poor quality (using OpenCV's Laplacian) or the absence of symbols, the user was prompted through voice instructions to retake the photo. Additionally, the "Symbol Selection" step was automatically skipped, and recording began if only one symbol was detected or if the user selected the "group recording" option during "Create Note." Similarly, during "Read Note," the system automatically enters the reading recording stage if a single symbol or "group recording" was detected. These design features were developed to address the specific needs of the BVI people and enhance their overall user experience.

To provide real-time feedback, the mobile app interacted with the backend server that we developed, which was built upon the Python Flask framework and utilized socket.io for real-time event-driven communication with the front-end. Our system used the multi-cloud developer data platform, MongoDB Atlas, to manage the user data with privacy and security.

4.2 3D Printing Pen

Following the user feedback, we've improved the accessibility of 3D printing pens for BVI people by selecting the most appropriate 3D printing pen, utilizing materials with strong adhesion, and addressing auditory perception deficiencies through pen modifications.

4.2.1 ***3D printing pen and materials selection****.* The market offers two types of 3D printing pens: high-temperature and low-temperature pens. *High-temperature pens* possess the capability to handle materials with melting points above 180°C, including ABS and PLA. However, because of their high temperature, the newly printed materials are unsuitable for immediate handling until they have cooled down. In contrast, *low-temperature 3D printing pens* are specifically designed for children and have limited filament options, such as PCL or eco-plastic strands, owing to their lower operating temperature. This design allows users to touch and mold the printed object during the printing process before it solidifies. We suggest using low-temperature 3D printing pens at around 50°C for BVI people. This safe and convenient tool enables engaging in DIY projects, exploring artwork, and correcting printing errors easily

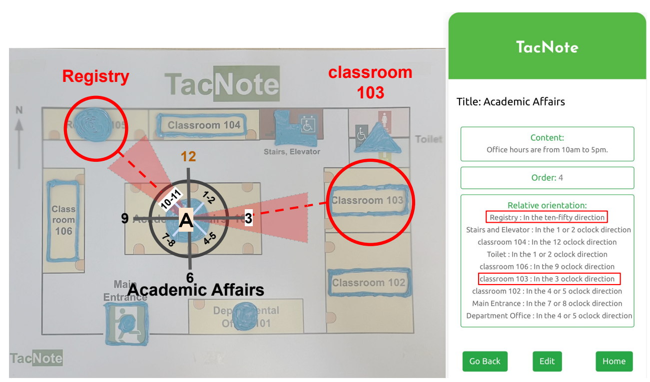

Figure 8: The method of displaying relative orientation. Left: Academic affairs (A) is selected as the central point, and eight directions are presented using the clock method to show their relative orientation to A. The right side shows the information on the second layer of TacNote. The registry is located in the ten-fifty direction from A, and Classroom 103 is located in the 3 o'clock direction from A.

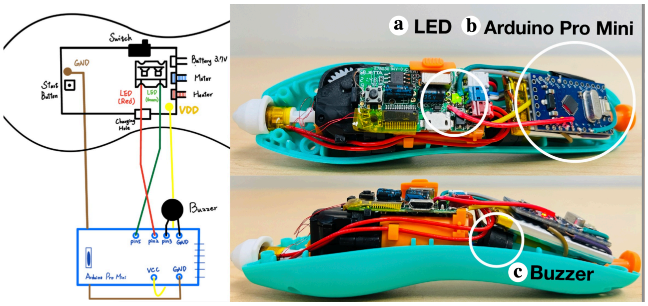

Figure 9: Circuit connection and a modified 3D printing pen. Left: Simple circuit connection between an Arduino Pro Mini (Fig. right b), a buzzer (Fig. right c), and an LED light (Fig. right a) on the 3D printing pen. Right: Displays a dismantled and modified 3D printing pen.

by removing and redrawing incorrect notes. For our prototype, we selected 3Doodler Start+ [1].

For materials, eco-plastic strands are used as filament material for low-temperature 3D printing pens, easily removable from most surfaces [1]. However, they lack adhesion, which poses a challenge during drawing. To address this limitation, PVC plastic sheets or PVC tapes are recommended to ensure the complete adhesion of tactile images. Plastic-based products are also suitable for those who prefer easy removal from the drawing surface.

4.2.2 ***Modification to the 3D printing pen.*** The original design used an LED display to indicate different states, such as whether it was heating or low on power. However, this was not user-friendly for BVI people, and feedback from the formative study confirmed this issue. To address this, we connected an Arduino Pro Mini microcontroller [4] to the LED display of the 3D printing pen and added a buzzer that emits different frequencies of sound when receiving different signal changes. We assigned the red light (means the pen is not heated sufficiently yet) to emit a single beep with an audio frequency of 1397 Hz, the green light (means the pen can be used) to emit two ascending beeps with frequencies of 1175 Hz and 1245 Hz, and the yellow light (means the pen has low power) to emit two descending beeps with a frequency of 1245 Hz and 1175 Hz. The circuit connection diagram and modification diagram are shown in Figure 9. These modifications make the 3D printing pen more accessible and usable for BVI people.

5 USER STUDY

Through this user study, we aimed to understand: (i) How is the usability of TacNote, and (ii) whether the proposed BVI improvement dealt with the users' daily tasks.

5.1 Participants

As in the formative study, we sent invitations through the authors' connections and public recruitment posts on social media. We recruited ten BVI people (five men and five women), aged between from 25 and 50 (mean=33.7). They did not participate in our formative study. Of the participants, nine were blind, while one had one eye with a vision of 0.01, and the other eye was blind. Four of the blind participants were blind since birth, while the others lost their vision later in life. Additionally, eight of the participants had no experience of using a 3D printing pen, and only two of them had some experience of using a 3D printing pen. This information is summarized in Table 3. By intentionally recruiting participants from diverse professional backgrounds and interests, we aimed to obtain a comprehensive understanding of how BVI people utilize TacNote. Through this approach, we could gather valuable insights into the unique ways in which TacNote is utilized by BVI people from different walks of life. In the subsequent sections, we will refer to our BVI participants as P1-P10.

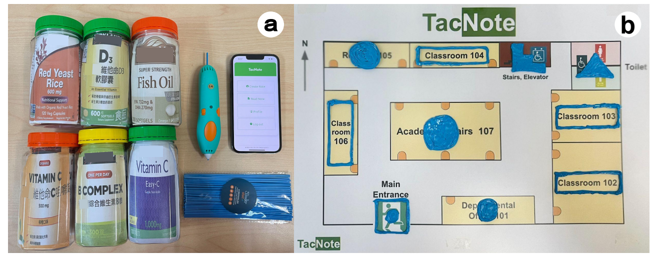

Figure 10: Task material and equipment. (a) Equipment used for Task 1, including six bottles of similar size and shape, a 3D printing pen with filaments, and a mobile phone. (b) Equipment used for Task 2, mainly consisting of a tactile map with pre-drawn shapes and a mobile phone.

5.2 Task

We devised two tasks to assess the efficacy of TacNote for BVI people. The first task, "Similar Item Discrimination," was the most frequently mentioned application in our formative study. The second task, "Spatial Understanding," falls under the category of "Comprehension of Graphics" applications, which was identified as the second most commonly mentioned category in our formative study. We selected two tasks to encompass TacNote's full functionality, and the third category's complexity lies between these tasks. To prevent fatigue from repetitive actions, we chose the two most common types that participants encounter in their daily life. Additionally, these tasks encompassed a wide range of TacNote's functionalities. Both tasks aimed to evaluate the efficiency and effectiveness with which BVI people can use TacNote to complete. For both tasks, we have created a scenario and a subsequent 6-to-7-questions test to measure the participants' memory, task familiarity, and comprehension speed during the tasks, while also comparing their performance and approach to similar tasks in the past to identify the potential advantages that TacNote might provide.

5.2.1 ***First Task: Similar Item Discrimination.*** In the Similar Item Discrimination task, we used common vitamins and supplements as the scenarios presented to the participants. Six plastic bottles that were identical in size and shape were labeled with common vitamins and supplements available in the market, as illustrated in Figure 10 a. The researchers took on the role of family members and provided the participants with information about the item that they selected, which the participants recorded using TacNote. The participants were allowed to ask for information as many times as needed during the recording period. To assess

ID	Gender	Age	Vision Level	Occupation	3D printing pen Use
P1	Woman	25	Blind, since birth	Student	Never used before
P2	Woman	28	L:Blind, R:0.01, later on	Digital AT instructor	Have experience
P3	Man	31	Blind, since birth	Lector	Never used before
P4	Man	50	Blind, later on	Social worker	Never used before
P5	Woman	39	Blind, later on	Project staff	Never used before
P6	Woman	33	Blind, later on	Singer	Never used before
P7	Woman	37	Blind, later on	Unemployed	Never used before
P8	Man	32	Blind, since birth	Transcriptionist	Never used before
P9	Man	27	Blind, since birth	Music Producer	Have experience
P10	Man	35	Blind, later on	Service	Never used before

Table 3: Participant demographics for user study.

how the participants utilized TacNote when there was a significant amount of information to recall and to prevent biases arising from differences in the short-term memory capacity, the researchers provided oral information for each item, including the item name, main function, precautions, expiration date, and usage order. To test the participants' ability to accurately identify items and recall information in a situation where there were many similar items, we mixed up the positions and order of the bottles during the test, as mentioned in the formative study where the participants often struggled to locate items that had been moved. We created six questions to evaluate participants' ability to recall information quickly and accurately, and their capability to identify specific items among similar ones. The questions focused on item name, main function, precautions, expiration date, and usage order. Examples include: "Find the new Vitamin C." and "What is the usage order for Vitamin D3?" By doing so, we aimed to gauge the extent to which TacNote reduced the memory burden on the participants in a complex and information-rich scenario.

5.2.2 ***Second Task: Spatial Understanding Map***. In the Spatial Understanding Map task, we designed a scenario for the participants to familiarize themselves with the spatial layout of a new campus. The scenario aimed to simulate the experience of a visually impaired person who relies on verbal descriptions or uses a teacher's handmade maps to navigate a new environment. To achieve this, we used a 3D printing pen to create tactile graphics on the floor plans of the teaching building in advance (Figure 10 b) and recorded information about each location in TacNote, including the location name, description, order of document submission, and relative orientation display. We assumed that the participants were freshmen who would be taking courses and submitting documents on the first floor of the teaching building in the future. To assist the participants in becoming acquainted with the new environment, we provided a tactile map and TacNote with detailed content information. After the participants explored TacNote on their own, we administered a test consisting of seven questions about the classroom location, description, relative orientation, and document submission order. The questions included "Find class 104." and "In what direction is class 102 from class 104?" The test was designed to evaluate the participants' memory capacity, including their ability to retain content, comprehend information more easily when working with sighted people, and the extent to which TacNote reduced their memory load.

5.3 Procedure

Our user study consisted of three parts: instruction, task, and semi-structured interview.

5.3.1 ***Instruction***. Because of the fact that eight out of the ten participants had no prior experience with 3D printing pens, and those who had experience (P3 and P9) had used different tools in the past, we provided a tutorial at the beginning of the experiment. The tutorial included instructions on how to use the 3D printing pen as well as a tutorial on the TacNote system. Similar to the formative study, the participants were taught how to use the 3D printing pen to draw freely and were given 5-10-min of practice time. After completing the tutorial on the 3D printing pen, we proceeded to teach the participants about the TacNote system. Before introducing the system interface, we asked the participants to draw two tactile symbols of their choice (e.g., O and X), and after they finished drawing, we introduced the system interface while simultaneously asking them to label the symbols that they had just drawn. The system tutorial included all of the process steps (as shown in Figures 5a to 5h). Following the tutorial, we provided the participants with a 5-10-min break.

5.3.2 ***Task***. The tasks for this study were Similar Item Discrimination and Spatial Understanding-Map. For the first task, the participants were required to complete the entire process, from drawing tactile graphics to recording, repeating, and applying the record (Figures 5a to 5h) on their own. The recorded information included at least the title, content, and sequence of the task. For the second task, the participants were required to explore the tactile map, read the record, and apply their findings (Figures 5f to 5h) using TacNote without any explanation from the researchers. The exploration time was not limited and depended on the participant's personal habits. The recorded information included all of TacNote's functional items (title, content, order, and relative direction). The participants were given a break of 5-10-min before the tests to reduce the bias caused by short-term memory. To help the participants photograph, we provided a phone stand for option. Four participants used the stand and successfully took photos. The remaining six, familiar with photography, opted not to use it. Some of them attached the phone to the target object and moved it upwards to a distance they were comfortable with, around one palm's length or their accustomed shooting distance.

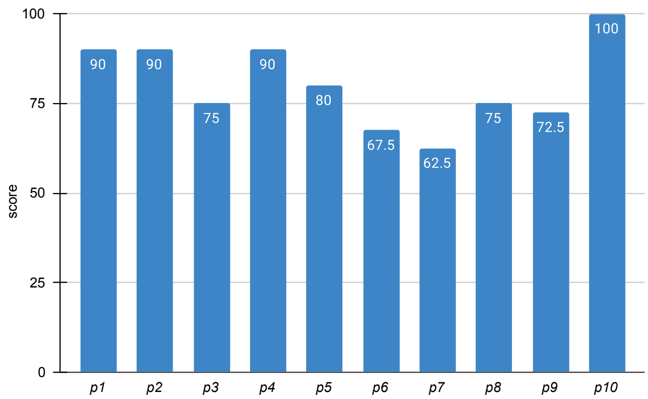

Figure 11: Ten participants' SUS scores. The ten participants scored TacNote using SUS, with an average score of 80.25 out of 100. Eight participants scored above 70, indicating high usability and effectiveness in meeting user needs.

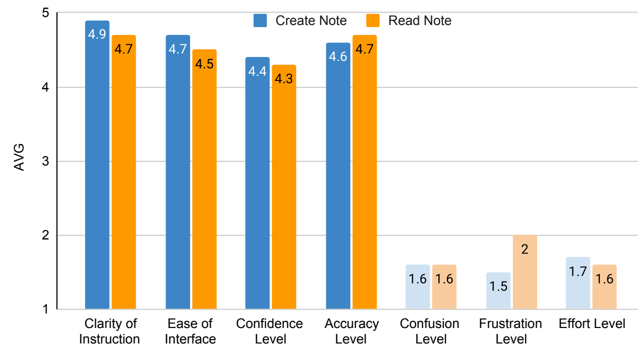

Figure 12: Create Note & Read Note score. Participants highly rated the TacNote system interface and instructions for clarity, ease of learning, confidence, and system accuracy (above 4 and close to 5). Negative scores for difficulty, frustration, and perceived time consumption were low, not exceeding 2.

5.3.3 ***Semi-structured interview.*** In conclusion, we conducted semi-structured interviews to gain insights into participants' usage of TacNote and their feedback on the system. We utilized the System Usability Scale (SUS) [9] to assess the system's usability for the participants and used open-ended questions to gather their ratings and feedback on the different steps (Create Note & Read Note), tasks (task one and two), and the overall system. To ensure clarity and consistency in responses, we used the Likert five-point scale, which is widely used in research contexts, as the evaluation criteria for the open-ended questions. This approach allowed us to gather valuable data to improve TacNote's user experience and overall system performance.

5.4 Results

5.4.1 ***System Usability Scale.*** In our study, we used the evaluation criteria suggested by Bangor et al. [5] to evaluate the usability of TacNote, utilizing the SUS score. The SUS score was computed by adding up the scores of ten questions and then multiplying by 2.5, with a maximum score of 100. Figure 11 illustrates the individual SUS scores of the ten participants who used TacNote. The results of our study showed the majority of the participants rated TacNote's usability as "good" or higher, with some achieving excellent scores. P5's score of 80 was a commendable rating, while P6's and P7's lower scores still fell within the acceptable range. The average SUS score of 80.25 indicated that TacNote had a high level of usability, suggesting that users found it easy to use and effective in meeting their needs.

5.4.2 ***Create Note and Read Note.*** To assess the participants' performance in the "Create Note" and "Read Note" operations, we used the Likert five-point scale and computed the average scores for each task across the ten participants. Figure 12 presents the results, with positive items displayed in a dark color and negative items in a light color. Higher scores indicate better performance. The positive scores for both tasks were above 4 and close to 5, indicating that the participants found the TacNote system interface and instructions to be clear, easy to learn, and were confident in using the system. They also gave the system a score of 4.6 or higher for accuracy. The negative scores for both tasks did not exceed 2, suggesting that the participants did not experience difficulties or frustration or perceive the system to be time-consuming. However, the negative scores were mainly due to the participants facing challenges in capturing photos for recognition during the Create/Read Note process. The overall negative scores were slightly higher for "Read Note" than for "Create Note," with a higher frustration level. Note that the degree of frustration with taking photos might depend on an individual's familiarity and experience with photography. As reported by most participants, they found it took more time and effort to take good photos despite the initial photo quality tips provided by the system, which contributed to the feelings of frustration.

In the task evaluation, we also used the Likert five-point scale as the rating criterion to measure the participants' performance on four dimensions across two tasks: (i) understanding of the task objectives with TacNote, (ii) frequency of encountering similar situations in the past, and (iii) the level of assistance provided by TacNote as compared to that provided by the past methods used in similar situations.

In Task 1, which was Similar Item Discrimination (see Figure 13 left), all ten participants gave TacNote's help and understanding of similar bottles received a high score of 4.9. The average score given by the participants regarding their past experience encountering this task situation was 3.6. However, two participants, namely P7 and P1, gave a score of 1, indicating that they had no prior experience in this situation. P7 recently lost her sight and had not encountered similar situations before. In contrast, P1 mentioned that *"I usually buy different bottles directly, but with the help of TacNote, I can buy similar bottles without specifically looking for different-shaped ones."*. Among the participants who had encountered similar situations in the past, TacNote's assistance was rated 4.875 as compared to that of the methods that they had used before. P2 and P5 pointed out that people might forget what was stored in a bottle over time, irrespective of its shape. TacNote could assist in remembering the contents by providing a note-taking system. P3 and P4 shared that *they typically used stickers or rubber bands to distinguish between stored items, but they found these methods to* *be limited in terms of the information that they could provide.* P3 expressed that TacNote offered real-time access to more information. In addition, P6, P8, and P9 also mentioned that the system could record a lot of information, making it more than just a bottle.

Furthermore, an additional measurement was added to this task to understand the participants' personal memory performance: the corresponding results are shown in Figure 13 (right). On average, without the system, the participants rated their memory retention ability at 2.4, whereas with the system, the score increased to 4.9. The participants mentioned that without the system, they could remember the name or quantity, but they might forget or could not recall more complex information such as expiration dates or large quantities. With the system, P3 and P9 said *"we don't need to remember, we can directly use the system to know all the contents,"* P4 and P10 mentioned *"if we accidentally forget something, we can check it with the system,"* and P5 said, *"because even if I can't remember the symbols, there is still a system to assist."*

In Task 2, Spatial Understanding-Map (see Figure 13(left)), all participants gave the TacNote system received a full score of 5 for the level of assistance and understanding provided in the map task by all ten participants. Each participant had prior experience in this scenario, with an average frequency of 3.8. The TacNote system was highly rated with a score of 4.6 for its level of assistance as compared to the past tools used. The participants described the past methods for solving map-related tasks as being either verbally described by others or by drawing simple maps on the palm of their hand with their index finger. Some larger units provided tactile maps, but these still required at least two separate pieces of paper to represent the map and legend, and repetitive comparisons to understand the spatial concepts, which was time-consuming and laborious. P2, P3, P4, P6, P7, P8, and P10 expressed that the system's ability to indicate relative orientation helped them better understand spatial distribution. In particular, P2 stated that "using clock notation is like zooming in on the entire map." Additionally, P3 and P6 mentioned that TacNote allowed for the recording of more detailed information, which could be more flexibly applied. P1, P2, and P9 found the system's ability to provide immediate location information to be

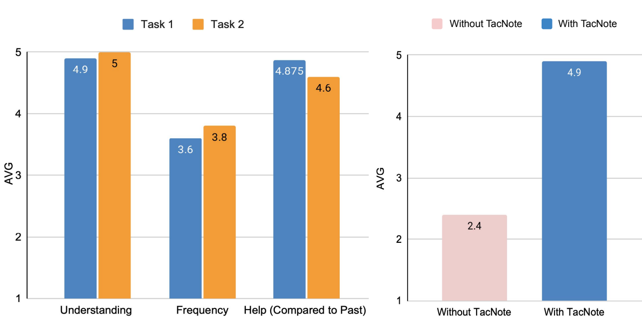

Figure 13: Task 1 and Task 2 scores and Task 1 personal memory score. Left: TacNote was highly rated for its assistance in both Task 1 (4.875) and Task 2 (5), scoring significantly higher than the previous methods used (above 4.6 for both tasks). Right: Task 1 showed a significant increase in the participants' memory retention ability, with the score increasing from 2.4 to 4.9.

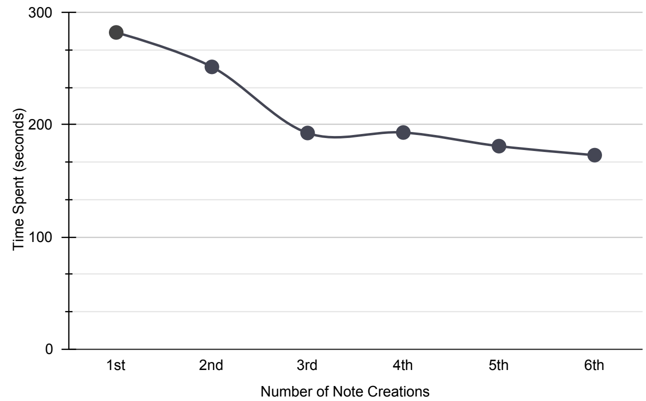

Figure 14: Create Note learning curve: Rows represent the creation of the first note versus the sixth note, and columns show the average time taken by ten participants to create notes in Task 1. The graph shows a 109.3s difference between the first and the sixth notes, indicating TacNote's user-friendly interface and potential for improvement with practice.

very helpful, with P2 stating, *"In the past, constantly referencing the legend on the map was very troublesome,"* and P9 saying, *"Sometimes when I touch tactile maps, I become absent-minded, forgetful, or don't want to look, but now with TacNote, I can just use my phone to take a picture and tell me the content."*

5.4.3 ***Time spent.*** All of the participants successfully completed the test questions in both tasks. TacNote provided instant auditory feedback via a screen reader when it recognized the note, enabling the participants to quickly identify if they had found the wrong target object and continue their search for the correct one. The average time for a participant to create six items in Task 1 was 217 seconds, which varied on the basis of their individual familiarity and habits with taking photos and inputting information. Task 2 involved exploration, with times ranging from 284 to 1274 seconds (average of 10 minutes) depending on each participant's personal habits. By analyzing the average time it took the ten participants to create notes from the first to the sixth note, we created a learning curve graph (see Figure 14) that showed a difference of 109.3 seconds between the time that it took to create the first note versus the sixth note, indicating that TacNote's interface was user-friendly and the usage speed can increased with familiarity. Additionally, we analyzed the response times and performance of the participants in both task tests. Three items were calculated: responses through touch only, responses using TacNote, and minimum and maximum TacNote responses.

Table 4 shows that the participants required various amounts of time to find the targets in Task 1. The participants who spent less time mostly used their own tactile graphics to filter out the first layer of information. For the participants who spent more time, in addition to personal differences in photographic ability, some of them did not specifically remember the corresponding items of their own tactile graphics but searched for possible items through TacNote. The average time spent on task answering ranged from 46 s to 147.5 s.

Title/Time	Direct Answer	Answer after Using System	Time Spent Using System (Fastest/Slowest)
Finding the target	6.7 s (4 people)	147.5 s (6people)	48 s / 340 s
Content	None	45.9 s (10 people)	30 s / 132 s
Dosage	4 s (1people)	76.7 s (9 people)	29 s / 190 s
Effective date	2 s (1people)	92.5 s (9 people)	23 s / 200 s
Precautions	4 s (1people)	85.95 s (9 people)	38 s / 218.6 s
Administration order	None	81.4 s (10 people)	18 s / 299 s

Table 4: Time spent on Task 1 in our study.

Title/Time	Direct Answer	Answer after Using System	Time Spent Using System (Fastest/Slowest)
Location	5.9 s (6 people)	88.3 s (4 people)	30 s / 210 s
Content 1	None	49.1 s (10 people)	25 s / 83 s
Content 2	None	52.2 s (10 people)	38 s / 102 s
Direction 1	None	62.1 s (10 people)	34 s / 101 s
Direction 2	21 s (1 people)	65.8 s (9 people)	34 s / 106 s
Direction 3	10.5 s (2 people)	89.2 s (8 people)	25.96 s / 307 s
Order	16 s (1 people)	62.3 s (9 people)	28 s / 130 s

Table 5: Time spent on Task 2 in our study.

The time spent on Task 2 (see Table 5) showed that half of the participants could directly answer the location of the classroom on the top floor after exploring with TacNote. Apart from individual differences in memory ability, this indicated that TacNote could help the participants understand and remember location information without the assistance of a third party. For those who completely forgot, all of the participants were able to search through all of the locations in approximately 200 seconds. For Tasks 2 to 6, which involved more complex information, most of the participants used TacNote to answer the questions, taking an average of 50 to 80 seconds per question. Longer durations were also attributed to not immediately determining the location and exploring multiple locations with TacNote before finding the target.

5.5 Findings

On the basis of the feedback provided by the ten participants in our user study, we identified four major findings:

Memory burden reduction: Six participants (P3, P4, P5, P6, P9, and P10) mentioned that TacNote freed their worries about forgetting via the direct access to the content. P3 specifically mentioned, *"With TacNote, you don't have to memorize every detail, right?"* Additionally, P1 stated, *"Because TacNote provides additional descriptions, it can reduce my memory burden."*

Customizability: All of the ten participants provided positive feedback on TacNote's ability to customize tactile symbols and content. These included the following: (1) **Symbols**: The participants mentioned that in the past, marking tools had very limited changes, but with TacNote, they could use a 3D printing pen to choose their favorite shapes and symbols that were easy to associate without limitations (Figure 15). In particular, P4 said, "*Drawing my own symbols is better because I know what they mean, and it can help me recognize them. And (TacNote) can also record detailed explanations.*" Additionally, P2 mentioned that the universality of being able to customize tactile graphics was better. (2) **Content.** The participants mentioned that they liked the ability to add and edit content and to provide different levels of detail for different symbols depending on their own preferences. In particular, P5 said, "*It's better not to have to change tactile Symbols, but to be able to edit the content directly, which I prefer.*"

Figure 15: Works of the ten participants in Task 1 are displayed using the symbol of fish oil. It can be seen from the participants' works that each person's labeling of the symbol for fish oil is different, including letters, graphics, Braille, and basic shapes

Independence: TacNote enabled the ability to review information independently without needing help from others. Both P2 and P3 agreed that TacNote allowed them to avoid having to ask others and instead enabled them to repeatedly review the information that they want to understand.

Convenience: We observed that TacNote supported the following: (1) **Hierarchical organization of data.** Both P4 and P10 both provided positive feedback on TacNote's ability to provide layered information. In particular, P4 stated, "*It's attractive to be able to decide when to listen to less or more content,*" while P10 also expressed appreciation for this feature. (2) **Auto generating directions.** P2, P3, P4, P6, P7, and P8 all agreed that the function of automatically generating directions could better help them understand spatial relationships. (3) **Richness of audio feedback.** P3, P4, and P6 provided positive feedback regarding TacNote's provision of audio feedback. P3 emphasized that the sound effects could let him know whether his operation was correct, while P6 mentioned that it enabled him to quickly understand what object he was touching. Additionally, P4 mentioned that the sound of the 3D printing pen was great and could be operated independently.

The feedback from the ten participants confirmed that TacNote's provided features could effectively assist BVI people, offering a promising solution to enhance their access to information.

6 DISCUSSION AND FUTURE WORK

The user study that we conducted confirmed TacNote's ease of use. The participants' feedback indicated that our core concept and features met their expectations and design goals. TacNote reduced memory burden, offered customizability, promoted independence, and provided convenience. In addition to the task scenarios that we presented in the user study, participants mentioned other personal situations where TacNote could be helpful, such as buttons on a remote control, documents, books, or storage boxes. They also suggested educational applications, such as origami instructions, geography maps, and textual tutorials, which aligned with the use cases identified in our formative study (B1-B5). These findings demonstrated that TacNote was versatile and could address a variety of situational challenges.

However, our experiment revealed that users' familiarity with mobile devices and photography skills greatly influenced their user experience and smooth usage. Even with retake photo prompts, sound guidance, and phone stands provided by TacNote, some participants still faced challenges in adjusting angles and aligning captures correctly. Prior research emphasized challenges faced by BVI people in capturing high-quality photos and proposed techniques to guide them [2, 25]. Moreover, previous studies have explored using phone tripods to assist BVI people in recognizing 3D models [45]. In the future, TacNote could enhance camera and lens functionality, offer comprehensive guidance prompts, and provide assistance to ensure a smoother camera experience for BVI users.

Furthermore, we acknowledge a technical limitation in our study regarding the color threshold, set to a narrow range corresponding to the blue filament. This may cause detection errors when background colors are within this range. In future work, we plan to address this issue by enabling customized color filaments.

Apart from the limitations, the participants expressed their desire for additional features in the future. P2 suggested a "sharing" function to share note information and tactile graphics with others, useful in public places, art museums, campuses, and for teaching by visually impaired educators. in addition, P4, P9, and P10 suggested incorporating common labels such as Braille or QR codes to format frequently used or repetitive symbols and text, expediting the note-taking process. The 3D printing pen could create custom symbols, offering a comprehensive range of tactile options. To further accelerate the recording process, we could create fixed forms or stickers of commonly used symbols, such as letters, numbers, basic shapes, or Braille.

7 CONCLUSION

In this paper, we presented TacNote, an interactive solution enhancing information access for BVI people. TacNote enables them to create tactile graphics and define content independently by using a modified 3D printing pen. Using TacNote's camera-based mobile app, the users can interact with tactile symbols in real time, facilitate the creation, and modify records. In addition, TacNote's layering and automatic relative positioning features support repeated exploration. We conducted a formative study with five BVI participants and a user study with ten BVI participants to identify the needs and usability of a 3D printing pen-based method. The feedback showed that TacNote significantly reduced memory burden, offered customizability, promoted independence, and provided convenience. We discussed the applications of our method beyond labeling and identification to learning, teaching, and spatial understanding.

ACKNOWLEDGMENTS

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