LightWrite: Teach Handwriting to The Visually Impaired with A Smartphone

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ABSTRACT

Learning to write is challenging for blind and low vision (BLV) people because of the lack of visual feedback. Regardless of the drastic advancement of digital technology, handwriting is still an essential part of daily life. Although tools designed for teaching BLV to write exist, many are expensive and require the help of sighted teachers. We propose LightWrite, a low-cost, easy-to-access smartphone application that uses voice-based descriptive instruction and feedback to teach BLV users to write English lowercase letters and Arabian digits in a specifically designed font. A two-stage study with 15 BLV users with little prior writing knowledge shows that LightWrite can successfully teach users to learn handwriting characters in an average of 1.09 minutes for each letter. After initial training and 20-minute daily practice for 5 days, participants were able to write an average of 19.9 out of 26 letters that are recognizable by sighted raters.

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CCS CONCEPTS

• **Human-centered computing → Accessibility technologies**.

KEYWORDS

Accessibility, Handwriting Learning, Blind and Visually-Impaired Users

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1 INTRODUCTION

Even in the digital age, handwriting is still an important part of daily life [39]. Signing legal documents, writing expressive letters to friends, and leaving a note for the family all require basic handwriting skills. As pointed out by Huckins, handwriting is an intimate means of communication. *"It is a personal thing that's all one's own"* [15]. Moreover, being able to handwrite builds a feeling of self-confidence [8]. Learning how to write as a child, most able-bodied people take the ability of handing-writing for granted. However, for blind and low vision (BLV) people, handwriting is particularly difficult due to the lack of visual feedback [41], which makes the understanding and sketching of the shape of letters very challenging [40]. Although braille has been widely used for reading and writing for BLV users [18], it is not accessible for sighted people, isolating BLV users from smooth communication with others who don't understand braille. Although recent inventions such as Braille keyboards and displays worked in bridging the gap between BLV and sighted users to a certain extent, additional effort and payments are needed to install and utilize them. Moreover, the lack of knowledge of letter shapes often causes interpretation gaps between slighted and BLV people. Analogies like "U-turns" cannot be understood unless they have learned the shape of letters.

There has been a wide range of solutions to teaching BLV people how to write letters. One of the most popular ways is to use letter-shaped 3D objects, such as blocks, and ask BLV people to feel the shape of the letters [46]. Other technologies, such as TactiPad [48], which provide instant tactile raised lines after each drawing, can also assist with learning how to write. However, all of the existing solutions require additional hardware, and some of the advanced methods such as TactiPad are very expensive. There also exist specialist schools where BLV people receive training on writing their names [44]. However, such resources are very limited and require a sighted teacher to assist with the learning process [1].

In order to provide a low-cost and easily-accessible alternative to specially designed tools, we present LightWrite, a smartphone application that can teach BLV people the handwriting of 26 lowercase letters and 10 digits, and support their independence during the learning process without a teacher. Our system uses a voice-based teaching method that is only based on a smartphone and requires no additional accessories, thus introducing no additional cost.

Based on the results of a pilot study with BLV users (N=6), we designed a simplified font for English letters that can be easily understood and remembered by users. We also proposed a voice-based teaching method based on the font design to provide a series of easy-to-follow instructions for strokes. We conducted a formative study with the same users to better understand their needs when using our method. Then, we compiled our findings into a series of design implications, which we leveraged to build LightWrite. The system consisted of four modules, including a basic stroke module, a study module, a practice module, and a test module. Finally, we conducted a longitudinal user study (N=15) to evaluate the usability of LightWrite. After going through the basic stroke module and the study module on the first day, participants could write an average of 7.6 recognizable letters, while the average number of recognizable letters at the beginning was 0.9. Moreover, after 20-minute daily practice for the next 5 days, their performance continued to improve, reaching 19.9 out of 26 letters. Participants also provided very positive feedback on LightWrite as it provided an easy and convenient approach for them to learn handwriting, that they could have never imagined.

The main contributions of this paper are as follows:

- We present a new simplified handwriting font that consists of simple geometric shapes and a voice-based teaching method to facilitate BLV users' learning process for handwriting.
- Our formative study (N=6) identifies a series of design principles for the voice-based shape teaching method for BLV users.
- We propose LightWrite based on our design and the formative study outcomes, a handwriting teaching system consisting of voice instructions, haptic feedback, and four learning modules.
- Our longitudinal usability study (N=15) shows that after the training and practicing stage, BLV users could write 19.9 of 26 English letters that are recognizable by sighted raters.

2 BACKGROUND

We first review the existing teaching methods for BLV users to help them learn how to write. Then, we summarize devices and tools that have been used to support BLV users as they learn to handwrite. Since feedback is one of the most essential parts of the teaching procedure, we also review related work on feedback techniques for BLV users during writing and drawing.

2.1 Teaching Handwriting to BLV Users

The topic of how to teach BLV people handwriting has been investigated by researchers since the early 20th century [29]. Stakeholders such as teachers and educators proposed a range of methods to teach BLV people to write. Early in 1965, Huckins, working as a state school teacher, summarized her experience in teaching blind students handwriting with a paper and a pen Huckins [15]. She divided the 26 lower case English letters into seven categories: points (*i,t,u,v*), mounds (*r,n,m,x,v*), loops (*e,l,h,b*), tails (*j,y,z*), balls (*c,a,d,g,o*), s-letters (*s,k,p*), and reverse tails (*f,q*). Nowadays, this method is still widely used as a professional standard with very few modifications [23, 49]. Mccoy and Leader [33] proposed using oral clues and hand by hand tracing with a pen to guide BLV students to learn how to sign their names.

As digital devices are becoming prevalent, there are more and more teaching methods based on digital techniques, such as text entry [4, 30, 37, 45], gesture input [10, 21, 26, 31] and even programming [20, 34]. However, very few papers focus on teaching handwriting to BLV users using modern technologies beyond paper and pen. The most related work to our system is a multimodal system proposed by Plimmer et al. [40] for teaching blind children cursive handwriting to create a personal signature. The system adopted the concept of mimic and aided the teaching of signatures by translating digital ink from a teacher's stylus gestures to non-visual clue for BLV students to learn the strokes [41]. In contrast, LightWrite does not require the presence of a teacher and allows BLV users to learn handwriting on their own. We developed an intelligent algorithm to automatically recognize users' handwriting and provide appropriate voice-based instructions until users write a letter correctly.

2.2 Tools to Support Handwriting and Drawing for BLV Users

Besides handwriting teaching methods, the advance of accessible research and engineering also promotes a wide range of assistive technologies for BLV users [1–3, 19, 36]. Traditional tools, such as 3D physical blocks, can provide the tangible feel of the shape of characters [46]. Modern tools are starting to leverage more complex techniques to help BLV users. For example, Itoh and Yonezawa [17] developed a support system with a tablet and binaural headphones to provide sound imaging signals to help individuals handwrite characters and draw figures. Kurze [24] proposed TDraw, a system with a thermo pen and swell-paper to allow blind people to draw pictures and at the same time study their drawing process. Rassmus-Gröhn et al. [42] built a virtual haptic-audio drawing surface where users could draw on it and switch mode to touch the haptic figures. In McSig, Plimmer et al. [41] used an audio and haptic pen, as well as physical tactile lines on the paper to assist visually impaired people to follow the teacher on handwriting their signatures. Recently, Panotopoulou et al. [38] proposed a tool to 3D-print flat tactile line drawings to assist BLV users to better understand the shape of 3D objects. However, all of the previous work, including both traditional and modern tools, relied on external devices (*e.g.*, thermo pens, force pens, 3D-printers) that are not readily available in daily life, introducing additional learning costs for BLV users. To the best of our knowledge, LightWrite is the first system that does not require any additional devices, beyond a smartphone, to teach handwriting to visually impaired users.

2.3 Feedback for Accessible Handwriting and Drawing

The reason for building specialized teaching tools and systems for BLV users is to provide additional non-visual feedback. Researchers investigated two aspects of visual feedback alternatives for blind users to learn handwriting [41]: 1) feedback to assist with motor skills learning, and 2) feedback on a visual document. For the motor skill aspect, haptic guidance and constraints have been studied extensively [16]. Common guidance feedback involves pulling users' hand along a predefined trajectory to teach the handwriting of Latin letters [35] or Asian characters [13, 47]. As for visualizing a document, researchers have mainly explored several modalities. Haptic feedback is still the most common. For instance, Yu and Brewster [51] used a haptic constraint approach to enable BLV users to explore line graphs and bar charts by following the grooves. Sallnas et al. [43] used haptic interfaces and paired sighted and visually impaired children to explore 2D and 3D geometric principles. Other than haptic feedback, both speech and non-speech audio are often used to replace visual displays for blind people. Both Kurze [24] and Rassmus-Gröhn et al. [42] used speech when the user touched particular lines or shapes on a tactile drawing. More work has explored non-speech audio feedback [7]. For example, Sound-graphs [28] used continuously varying pitch to display two-dimensional line plots. iSonic [52] sonified map navigation by using violin sounds to indicate numeric data and stereo pan for left and right movement. However, most of the haptic feedback requires additional hardware to provide guidance or constraint. Therefore, LightWrite – built on only a smartphone – does not provide haptic guidance feedback. Instead, it uses simple vibration as an indicator if users move within a handwriting trajectory. Moreover, LightWrite also uses step-by-step speech audio feedback to provide clues during teaching.

3 TEACHING DESIGN AND ITERATION

To support visually impaired users who are learning to handwrite, we first identified the problems of directly applying the existing teaching methods on smartphones through a pilot study (Section 3.1). Then, we designed an structurally simplified handwriting font (Section 3.2) and a voice-instruction teaching method (Section 3.3) to facilitate the handwriting learning procedure. We conducted a formative study with a WoZ prototype to evaluate our design and compiled the findings into a set of system design implications (Section 3.4).

3.1 Problems of Existing Solutions

Due to the lack of visual feedback, it is hard for BLV users to understand the shape of a character. Even after learning the shape, another big challenge is to write out the perceived character correctly. Previous work mainly focused on two solutions to address these challenges: 1) following a predefined character trajectory [24, 32, 33], or 2) connecting grid dots to form the character's shape [27, 50]. However, as found in our pilot study, BLV users had complaints when using smartphones with these two solutions.

3.1.1 Participants. After getting the university IRB approval, we recruited six BLV users (2 female, 4 male, age mean = 24.8, SD = 1.57) for the design step. The recruitment and the following studies were all held remotely due to the Covid pandemic. Two participants were totally blind, and four had residual visions. All participants were smartphone users. All participants were native speakers of Chinese with basic knowledge of English. One participant reported having no knowledge of the shape of letters, while the rest reported having learned the shape of one or two letters from daily routines, but did not know the correct way to write or if the shape they learned was uppercase or lowercase. All participants reported knowing the shapes of at least a few digits.

3.1.2 Design and Procedure. We implemented two web-based prototypes for the existing two methods. The first prototype placed an English letter in bold Arial font (one of the most typical sans-serif fonts) at the center of the touch screen. Users need to start from the top and followed the stroke of the letter. A speech voice provided instructions on which direction to move, following the standard English handwriting stroke. The smartphone generated vibration as long as the finger was within 20 density-independent pixels(3.175mm) distance to the optimal path. The feedback would disappear once the finger moved out of the threshold distance. The second prototype placed 13 grid dots in five lines (3+2+3+2+3) in an interlaced manner and each English letter has unique traces to connect these dots. Note that these traces were designed to be interpretable for sighted people since our goal is to teach handwriting rather than text entry to users, which was different from techniques like EdgeWrite [50]. Users need to follow the trace to connect one dot after another. The phone provided vibration feedback once the correct next dot was reached, and audio feedback if users touched a wrong dot.

We conducted a remote pilot study with three of the six participants during the recruiting process. Participants were asked to explore with each prototype for around five minutes. For the first prototype, we explained how the prototype worked to the participants and asked them to explore it freely with the help of vibration feedback. For the second prototype, matte tapes were applied on the screen where the grid dots were, and we instructed participants to explore a sequence of dots indicating the shape of the letter.

The participants then attempted to connect the dots based on the sequence, and thus draw a modified shape of letters.

3.1.3 Results. A few themes emerged from participants' feedback. For the first prototype, participants reported two main issues: 1) It was hard to find the initial starting point; 2) The shape, especially the turning points, was hard to sense with the audio and vibration feedback. Participants reported a better experience with the second prototype. However, they often made mistakes when connecting two dots that were not in the same horizontal or vertical lines. After participants learned the actual shape of the letters, they reported being disappointed that the connected shapes using the second method deviated quite a bit from the true shapes. Moreover, P3 provided inspiring comments after knowing the shape of *b*: *"Why not just draw a half-circle from the bottom of the vertical line? Why bother to start a new curve in the middle of the line?"*

The pilot study provided a few important guidelines:

(1) The standard stroke process for characters is difficult for BLV users to follow and memorize. A simplified version of the characters is needed.
(2) Meanwhile, the shape of the character, especially the curvature, should be kept as close to the true shape as possible.
(3) Starting from a fixed point to write is difficult for BLV users. They should be allowed to start freely on the screen, like writing anywhere on a piece of paper.

3.2 Font Design for BLV Handwriting

Following the guidelines, we designed a new font that is especially simplified for BLV users. The standard handwriting of both English lowercase characters and digits consists of shapes that are not normally found in daily objects, thus hard to understand, describe, or write correctly. To address this problem, we adopted a block-like construction method of using three basic geometrical shapes to form the characters and digits in the Arial font: straight lines, circle, and hook. Using these basic shapes helped to simplify multiple-stroke characters and also maintained the recognizability of the characters, fulfilling the first two guidelines obtained from the pilot study. Moreover, we proposed to reuse the shape design of characters, when appropriate, to reduce the working memory requirement during learning. Figure 1 presents all the characters and digits in our font.

3.3 Voice-based Instructions Design

Following the design of the new font, we then proposed a set of voice-based instructions to teach the handwriting process for each character. All instructions were made in a progressive way. The instruction of a character starts with the description of the overall shape, followed by a step-by-step description of the writing procedure for each part of the geometric shape which forms the character. A sample instruction of letter *b* is like this: "Letter b is a tall character consists of a vertical line, and a right semicircle at the bottom-right of the line." "First, start from the upper left area of the screen, and write a long vertical line downwards. Do not lift your finger after." "Then, go right, and then upwards to draw a semicircle raised to the right, and close the circle to the middle point of the vertical line." Note that we intentionally obviated the need of starting from a fixed point. Users can start from anywhere they feel appropriate as long as they follow the general description in the instruction (*e.g.*, the upper left area of the screen for *b*).

3.4 Formative Study

To assess the validity of our design and obtain a better understanding of BLV users' learning process, we conducted a formative study with the same six participants. We aimed to identify the problems BLV people face when learning handwriting with the new font and voice-based instructions. We then compiled our findings into a set of design implications for the LightWrite system.

3.4.1 Design and Procedure. We implemented a WoZ prototype to support the remote formative study. The prototype consisted of three parts, an application on users' smartphones that collected and uploaded their touch trajectory data, a backend server that listened and stored users' data, and a web-based frontend for experimenters to visualize the handwriting.

During the study, participants learned all 26 lowercase letters and 10 digits in our specially designed font one by one, following the voice instruction from the experimenters. For each letter or number, the experimenter instructed the designed method of writing through a voice call, while the participants attempted to write the character on the screen. During the process, they could ask for clarifications and comment on the instruction. All users' handwriting data were captured by our server. After finishing each character, participants were asked to rate the overall difficulty of understanding and writing this character, on a scale from 1 to 5 with a step of 0.5(1, 1.5, ...). One indicated no difficulty at all, 3 indicated moderate difficulty, and 5 indicated that it was extremely difficult to understand and write the character. After they went through all the characters, the study ended with a brief interview to collect feedback on any issues during the teaching process.

3.4.2 Results. All participants successfully completed writing all 26 letters and 10 digits. The average perceived difficulty for each character was calculated and is summarized in Figure 2. The mean perceived difficulty for letters is 1.87 (SD=0.43) and 1.77 (SD=0.48) for digits. The most difficult letter is k (2.83 ± 1.29), and the ones closest to the average difficulty are n (1.75±0.99) and x (1.75±0.69).

More importantly, we observed some common issues among the participants during the study:

Initial Difficulties. First, all participants reported difficulties understanding the shape of some characters when first hearing the overall descriptions. They made confused humming sounds and asked a large number of questions to confirm their understandings. When writing in the middle of a letter, P5 reported that *"I have forgotten the rest of it."*. However, when proceeding to the phase with separate instructions for each stroke, participants were able to follow the instructions smoothly, write the correct shape, and reproduce the handwriting independently shortly after the instructions.

Urge for Feedback. Second, when writing the characters, many [5 out of 6] participants were constantly asking for feedback on their writing, such as "How was it written?" or "Am I writing correctly?" during and after following the step-by-step instructions. Some participants also felt insecure and helpless, and expressed

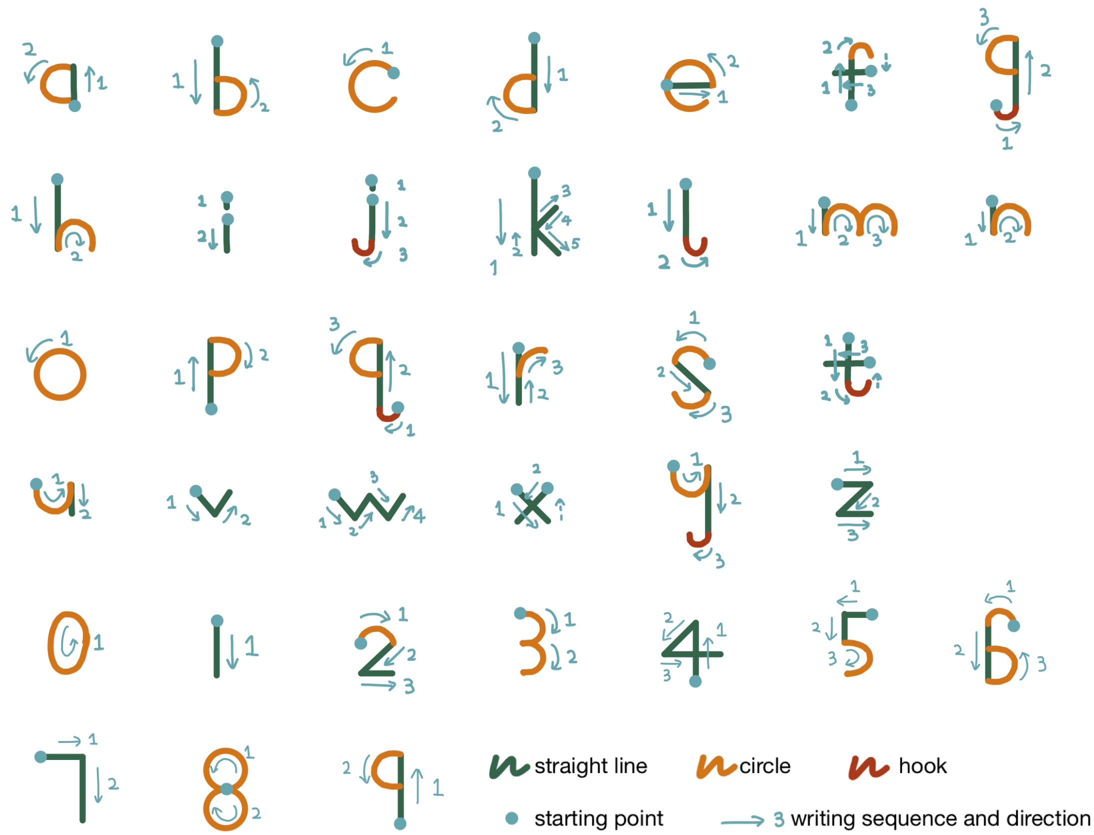


Figure 1: Font design of 26 English lowercase letters and 10 Arabian digits, with each character constructed by basic shapes of straight line, circle and hook.

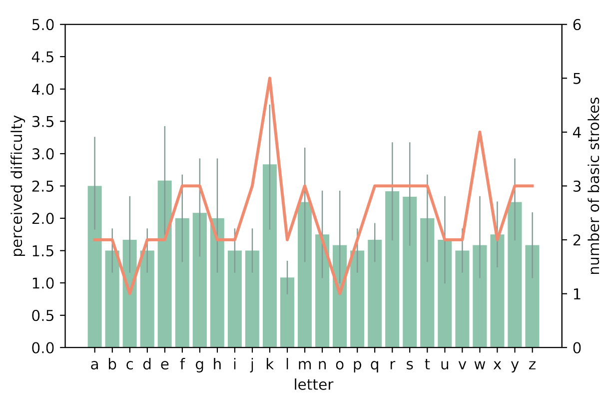


Figure 2: Bar plot of perceived difficulty of the 26 letters with error bar collected in the formative study, with the number of basic strokes needed to form the letter in the line plot overlaid.

their concerns during writing the process. For example, P2 worried about the circle he drew: *"I am just not sure if the circle was closed."*. Similar concerns were also observed on writing lines, as P1 expressed, *"I do not know how long is I should write the line.... I feel a bit insecure when I'm writing on my own."*. P3 proposed a feedback design to help correct their writing: *"(after writing a circle) I wish it could tell me how I failed in closing the circle, like 'the end of the stroke is at the down-right of the start'."* These concerns show that because of the consistent lack of visual feedback, BLV users need additional help to evaluate the correctness of their writing both during the writing process and after completing the writing.

Inconsistency between Understanding and Writing. The difference in prior ability in writing basic strokes also caught our attention. For example, when asking participants to write 45-degree diagonal lines, some participants had trouble writing it, even if they understood the shape correctly. We also found that it was difficult for them to correct their writing by simply using oral descriptions. This shows the gap between the process of understanding the shape theoretically and being able to correctly write the shape for BLV users.

3.4.3 Design implications. Based on these three major problems observed during the formative study, we summarized three design implications that we need to incorporate in our system:

(1) **Instruction needs to be fine-grained to reduce cognitive load**.
When provided with the complete instructions for a character all at once, users need to first memorize all of them, process them to understand the described shape, store each in the working memory, and then translate this knowledge to the handwriting. Such a long process introduces great cognitive load, as reflected by our first observation in Section 3.4.2. However, when instruction for each stroke is provided separately, users can focus on a single stroke instead of the whole character, which can significantly reduce the cognitive load.

(2) **Appropriate feedback at the endpoint of each stroke is crucial**.
Due to the lack of visual feedback, BLV users have uncertainty not only during the process but also about their final results. This could explain users' urge for feedback during our formative study. Therefore, additional assistance in both stages is needed. Specifically, prior to completing the character, feedback needs to be provided as a confirmation at the endpoint of each stroke. In addition, the end of the last stroke should be followed by the evaluation of the overall handwriting. Aside from providing useful information to assist writing, such confirmative feedback can also eliminate the potential sense of insecurity and helplessness.

(3) **Strict training for the basic strokes is necessary**.
Our descriptive instructions assumed that users could write out the basic geometrical shapes correctly. However, our study found a gap between having an understanding of a stroke as an abstract concept and being able to perform the writing accurately. To address this gap, we moved from descriptive instructions to strict training when teaching the basic strokes to ensure their correctness.
Since the basic strokes consist of three simple common shapes (*i.e.*, lines, circles, and hooks), such a design won't introduce too much burden for users, but can greatly improve their handwriting performance.

4 LIGHTWRITE SYSTEM DESIGN

Following the design implications generated from the formative study, we developed LightWrite, a system for teaching BLV users to write 26 lowercase English alphabets and 10 Arabic numerals. Figure 3 presents the overall structure of the system. It consists of five different modules: a basic stroke training module, a character learning module, a practicing module, a testing module, and a free-writing module.

4.1 Basic Stroke Training Module

Our results from the formative study illustrate the necessity of strict training for the basic strokes. In this module, LightWrite focuses on seven strokes consisting of the three basic geometric shapes that form the characters: short vertical line,long vertical line, oblique line from top left to bottom right, oblique line from top right to bottom left, circle, hook facing right, and hook facing left. Figure 4 present the seven basic strokes. Note that we omit horizontal lines and circles with different degrees (*e.g.*, the half-circle in *b* or the 270° circle in *e*) since they are analogous to vertical lines and the full circle.

LightWright allows users to start from anywhere around the screen center. When a user touches the screen, LightWright automatically generates the stroke to be learned, with the touchpoint as the top pixel of the stroke. At the same time, the system plays a voice instruction explaining the shape of this stroke. Then, the user follows the trajectory of the stroke, keeping the finger on the screen. During this process, the smartphone vibrates to provide haptic feedback, as an indicator that the user is moving the right way. If the finger moves too far from the standard stroke(>20 density-independent pixels, 3.175mm), the smartphone stops vibrating, reminding the user to alter the direction. The system plays a high-pitch bell sound once the finger reaches the end of the stoke. For the two hook strokes, an additional sound effect is provided at the turning points to remind the user to follow the curve.

4.2 Character Learning Module

The learning module is the most important module of LightWrite. It provides the curriculum where users learn the shape of the characters, practice handwriting, and improve their writing with intelligent feedback.

To simplify the learning process for the English alphabet, we divided the 26 letters into five groups (see Figure 5). The characters in one group have either identical shape but different orientations (*e.g.*, *b*, *d*, and *p*), or similar shapes with slight modification (*e.g.*, *i* and *j*), or close writing techniques (*e.g.*, *r* and *k*). Such grouping can help the user understand the shapes more easily and quickly. Moreover, to provide the curriculum in a sequence with increasing difficulty, the five groups are arranged in ascending order of the characters' average difficulty, *i.e.*, the mean of the perceived difficulties obtained from the formative study.

When the user enters the learning mode for a character, the system starts by playing the instruction that describes the overall shape of the character, followed by the instruction for the first stroke. Once the user finishes one stroke, the system plays the voice instruction for the next stroke, until the whole character is completed. The phone vibrates shortly at the end of each stroke to provide in-time feedback, corresponding to the second design implications.

After the user completes the character, LightWrite evaluates the overall performance and provides intelligent suggestions for the user to improve the writing. To provide automatic recognition of handwriting pictures, we trained two convolutional neural network (CNN) models, one for digits and the other for letters. Both models consist of two convolutional layers and two fully connected layers. A max-pooling layer, an activation layer with the ReLU function, and a batch normalization layer are appended after each convolutional layers. The model in the left part of Figure 3 visualizes the model for letter recognition. We recruited 18 sighted people and asked each person to close their eyes and write all

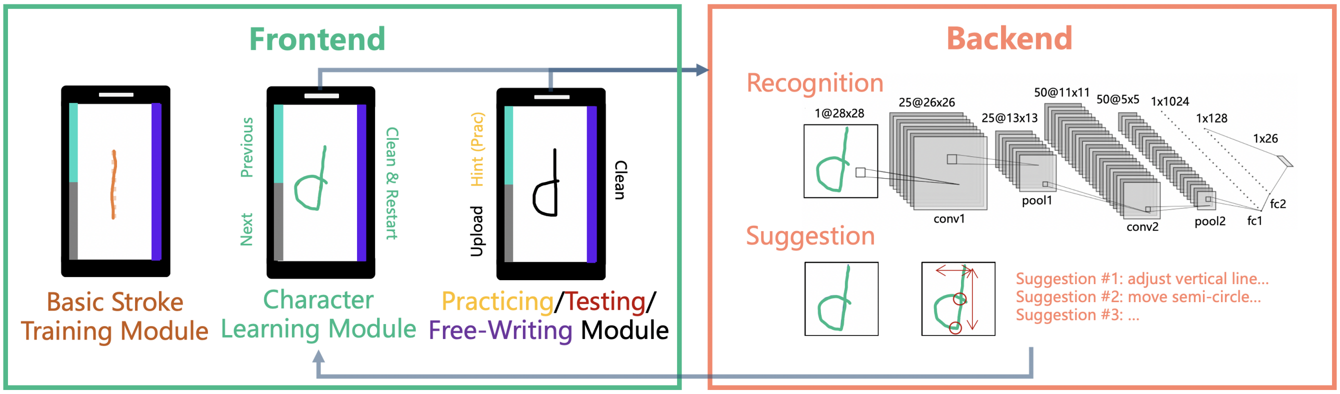


Figure 3: LightWrite System Overview.

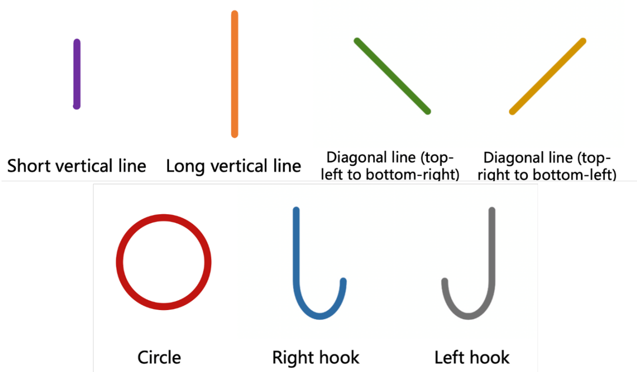


Figure 4: Seven basic strokes provided in the basic stroke learning module of LightWrite.

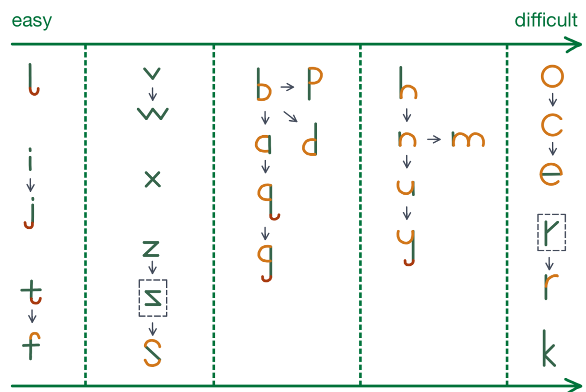


Figure 5: Grouping of the 26 English lowercase letters. The characters in one group have identical shape but different orientations (*e.g.*, *b*, *d*, and *p*), or similar shapes with slight modification (*e.g.*, *i* and *j*), or close writing techniques (*e.g.*, *r* and *k*).

characters 20 times. These data were combined with MNIST [25] and EMNIST [5] to establish a comprehensive dataset. Our final recognition accuracy on the testing sets which only include BLV users' handwriting were 91.8% and 91.5% for digits and characters respectively. When the user completes the handwriting, the picture of the handwriting is uploaded to the backend server and fed into the CNN model to get the prediction. The system then reports if the result is aligned with the actual character by voiced feedback. This provides the user with the overall evaluation of their writing.

In addition, based on handwriting teaching literature [9, 15], we developed a rule-based algorithm to diagnose common problems in the writing, and to provide appropriate voice-based suggestions, *e.g.*, the half-circle of *b* is not closed with the vertical lines, or the dash line of *t* is too high or too low. LightWrite keeps track of the whole stroke trace written by the user, which is also uploaded to the backend server together with the handwriting picture. Our algorithm analyzes the trace data, identifies strokes that are incorrect or have room for improvement, and reports with voice suggestions. The user can then leverage the suggestions to polish their writing.

These two different feedback mechanisms complement each other: the prediction feedback provides evaluations of whether the overall structure of the written character is correct or not, and the detailed feedback provides suggestions to correct or improve the handwriting.

The interface of the learning module supports a few functional gestures (see the second interface in Figure 3). To simplify the process of navigating through different characters, a short click on the upper-half or lower-half of the left edge area on the screen will trigger the name of the previous or the next character. Long pressing will move to the previous or next character in the same group. In addition, long pressing on the right edge area will clean the canvas and allow the user to re-write the letter from the beginning when they feel they have already gone wrong. Note that to trigger these functions, gestures need to start from the left/right edge area. This will prevent accidental triggers when the finger enters the edge area during the writing.

4.3 Practicing Module, Testing Module, and Free-writing Module

In addition to the two teaching modules, LightWrite also provides additional modules to augment the users' memory of the characters.

In the practicing and testing module, the user dictates a group of characters (either the five character groups or the whole character sets) to test their handwriting. When the dictation starts, the system calls out the name of the first character and asks the user to write that letter on the screen. Once finished, the user submits the picture, and the system calls out the next character. The order of the characters is randomized. In the testing module, after the user submits all characters, the system will report on the final evaluation of the characters. However, in the practicing module, in addition to the evaluation results, the system will also provide hints for the characters that the users do not write in a correct way, and the user will be asked to write each failed character again. The process repeats every time a character is written incorrectly until the user has failed three times. The system will then encourage the user to re-learn the character in the learning module (Section 4.2.

In the free-writing module, there is no group or character called. The user can write freely on the screen and submits the character they wrote. They can also leverage this module as a canvas and send a screenshot to friends.

The functional gestures are similar in these three modules. The upload of the current handwritten character for prediction is triggered by long-pressing the lower half of the left edge in all three modules. Long pressing the right edge clears the canvas. For the practicing and testing module, LightWrite will also replay the name of the character after the clearance. Moreover, in the practicing module, the user can long-press the upper half of the left edge to obtain a hint for the current character when needed.

5 USABILITY EVALUATION

We designed a two-stage usability study to evaluate LightWrite. In stage 1, we investigated how well LightWrite could teach BLV users handwriting when using the system for the first time. In stage 2, we further evaluated how LightWrite could help users learn and memorize how to handwrite the characters after using it for five days.

5.1 Participants and Apparatus

We recruited another 15 BLV users (8 female, 7 male, aged 25.3 ± 1.6) for the evaluation study. All participants were native speakers of Chinese and had basic knowledge of English. 6 participants were totally blind, and 9 had residual sight. None of them participated in the formative study or had learned handwriting lowercase English letters before. One participant reported having learned to write uppercase letters, and two other participants reported that they touched the shape of some letters a long time ago, but did not learn how to write. All participants reported knowing how to write the majority of the digits. Thus we focused on teaching letter handwriting in this study.

All participants were right-handed and used Android smartphones with screen readers to assist their daily usage. During the study, 12 participants used their left hand to hold the device. 10 of them usually wrote with their right index finger, 2 with their right thumb. Two participants used their right hand to hold the device. One of them wrote with the left index finger and the other with right thumb. Another participant placed the device on the table and wrote with the right index finger. Their usage pattern was largely determined by how they normally used their device.

5.2 Stage 1: Learning to Write

Stage 1 took place on the first day of the evaluation study. During this stage, participants went through the basic stroke training module and the character learning module to evaluate the usability and the effectiveness of LightWrite.

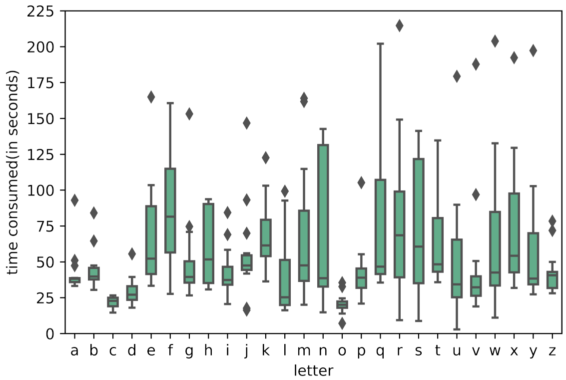
5.2.1 Procedure. The study was held remotely. Prior to using LightWrite, participants first went through a testing session (stage 0) to evaluate their handwriting ability. 26 letters were dictated in a random sequence, and participants were allowed to skip letters that they did not know how to write.

After the pre-test, participants spent 10-15 minutes to familiarize themselves with LightWrite. They started with the basic stroke training module until they reported that they had memorized all seven strokes. Then, they used the character learning module to follow the curriculum and learn all 26 lowercase English letters in a randomized order. For each letter, they needed to pass at least one handwriting trial that could be recognized by the system. The number of trials they tried for each character and the time for each trial were all recorded. After finishing all the letters, participants were asked to fill out a questionnaire with 11 items on a 7-point Likert scale. Four questions asked about the experience of learning handwriting with a smartphone in general, and seven asked their subjective feelings about LightWrite. At the end of the study, we conducted a semi-structured interview to collect more detailed feedback, starting with the following questions: What do you find learning handwriting with a smartphone meaningful? Do you have an idea of the shape right after listening to the instruction, or only after having finished a writing trial? Is there anything you like and do not like about the system, or is there any feature you would like this system to have? We extracted key points from the participants' responses, and summarized common beliefs from the statements. Stage 1 took around 90 minutes.

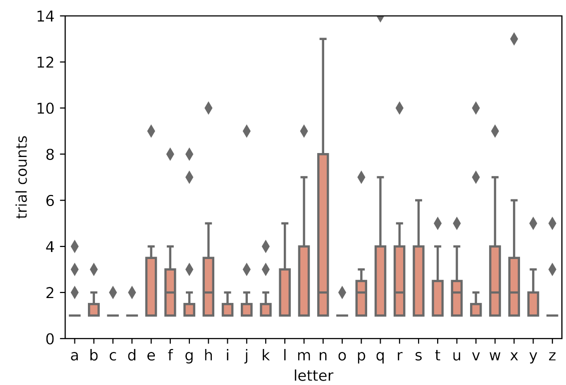
5.2.2 Results. All participants successfully completed at least one recognized trial for all letters. Using LightWrite, they learned handwriting quickly. After entering the character learning module, The average time from starting to learn to successfully write the character was 65.5 s (SD=24.8), including the time spent listening to the voice instructions.

Different letters took a different number of trials and time for participants to learn. Figure 6 shows the two boxplots. One-way repeated measure ANOVAs were performed with the letter as the main factor for indicating significance on both metrics ($F_{25,350}$(trial) = $1.959, p < 0.01, F_{25,350}$(time) $= 2.405, p < 0.001$). The letter that took the longest time to learn was *s* (mean=129.94±234.52 s); The letter that took the shortest time was *o* (mean=20.91 ±6.56 s).

Moreover, we also investigated the effect of the two eyesight conditions (being totally blind *v.s.* having residual sight). We applied two-sample t-tests on the data. The results do not indicate



(a) Time taken to learn different letters. The average time for a partcipant to learn a letter is 1.09 minutes, and varies for different letters.



(b) Number of trial taken to learn different letters. The average trial needed for a participant to learn a letter is 2.4, and also varies for different letters.

Figure 6: Stage 1 results for the participants to learn different letters. Few outliers outside of the y-scope was not shown on the graph for better visualization.

any significant difference in the average completion time ($t_{13} = -1.61, p = 0.13$) or the number of trials ($t_{13} = -1.47, p = 0.16$).

As for the questionnaire, all participants gave very positive ratings towards the idea of learning to handwrite on a smartphone (mean=6.4±1.0) and the user experience with LightWrite (mean=6.5±1.0). Figure 7 visualizes the ratings of each questions.

During the interview, participants positively acknowledged the value of learning letters and digits. Three themes of purposes for learning handwriting characters were identified as "interests in handwriting", "practical purposes" and "psychological needs". Eight participants reported having interests in learning handwriting, and ten acknowledged the practical value of learning handwriting. Regarding the psychological needs, two participants also mentioned learning handwriting could let them learn skills that were previously only available to their sighted counterparts, and one reported feeling a sense of achievement. When asked about potential cases where learning handwriting could be useful, participants were excited to provide many examples. P6 and P9 mentioned that this could help them to communicate with sighted counterparts using the letters to describe certain shapes. P4, P7, and P12 mentioned understanding the shape of characters on clothes such as printed logos and sentences. P3 also proposed that a handwriting input could be implemented such that the channel for auditory information would not be blocked while he tries to do input on devices, so that he could *"listen to music while typing if I want to"*. Six participants hoped they could learn Chinese handwriting with LightWrite.

Participants also liked the teaching features supported by LightWrite. Seven participants explicitly mentioned that the voice instructions with vibration feedback were the most helpful feature when using the system. *"[It] let me know when I have written crooked lines"* (P1). Having voice instructions divided into smaller step-by-step parts was also reported to provide *"a sense of security"* (P8). Participants provided insights to improve vibration modality. P9 suggested that *"additional speech feedback could be provided when I am writing off the standard stroke, such as 'you have deviated to the left'"*. P7 suggested a system to provide different vibration intensity to indicate the relative position of the current touching point: *"Maybe lower the vibration intensity when the touchpoint is approaching the edge of the standard stroke."* However, confusion still existed for some participants when trying to understand the shape. P2 and P6 reported being a bit confused when trying to imagine the direction of some semi-circles in the letter *q* and *h*. P10 expressed her concern in distributing the system to people with less geometrical knowledge for the descriptions such as "diameter" and "45°".

To further understand how voice instructions help users understand the shape of characters and build the knowledge of handwriting, we asked participants if they could form the image of characters immediately after listening to and understanding the descriptive instructions, or not until after following the instruction to write a complete letter, or if neither is the case. 7 participants reported that they could only generate the image after completing the letter following the instruction, 6 participants reported that they have a vague idea of the shape after hearing the instruction but can only form a complete image after completing one, and one participant(P13, totally blind) reported to be able to generate the image just by hearing the description.

5.3 Stage 2: Training and Memorizing

After participants used the two learning modules for the first time, Study 2 focused on the longitudinal teaching effectiveness when using LightWrite consecutively.

5.3.1 Procedure. After completing Stage 1, at the beginning of day 2, participants went through a second testing session (stage 1) to evaluate their handwriting ability prior to practicing. Participants were asked to use LightWrite 20 minutes per day for 5 days (day 2 to day 6). Finally, they went through a third testing session (stage 2) on day 7. We set the daily practicing time for 20 minutes to keep a balance between the floor effect and ceiling effect [6]. Participants could use any module in LightWrite and arrange the daily 20 minutes at their own learning pace. They were asked to note down

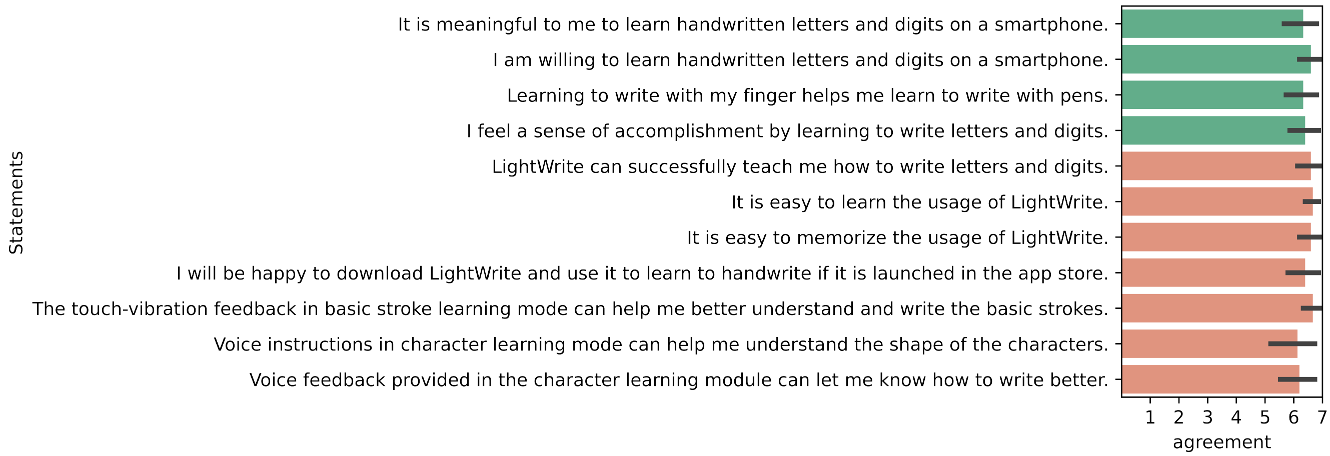


Figure 7: Bar plot of 15 participants' level of subjective agreement to the statements on a 7-point Likert scale. The participants generally hold a very positive attitude towards learning handwriting with smartphone as well as the LightWrite system.

their daily learning activities and send them to the experimenter. The goal was to learn and memorize the handwriting as much as they could during this stage. They were informed that on day 7, a final testing session would assess their learning outcomes, and that the top five who wrote the most letters would receive an additional $15 award. After the testing session on day 7, participants were asked to fill out a short questionnaire with three items on a 7-point Likert scale. Two questions asked how helpful the practicing module and the testing module were in assisting them in memorizing the handwriting for letters, and one asked for their willingness to recommend LightWrite to their BLV friends. Finally, we conducted a semi-structured interview to collect their feedback on using LightWrite on a daily basis, starting with the questions: What is your normal practice procedure? Have you felt frustrated during the process, and if so, what is the scenario? Finally, we asked them if there was anything they would like to add. Key points from the participants' responses were recorded. The whole Stage 2 took around 2.5 hours from day 2 to day 7. After the two stages, participants received $50 to $65 as compensation. The amount was based on their performance in stage 2.

5.3.2 Result. All 15 participants followed the study schedule and completed stage two. The main goal of teaching handwriting is to help BLV users to write letters that are recognizable by sighted people. Therefore, in addition to using machine learning models for automatic recognition, we further recruited two sighted raters to rate the three testing sessions (stage 0, 1, and 2). The two raters labeled all handwriting pictures of the three sessions independently (604 in total), and reached an agreement of $\kappa = 0.847$. Figure 8 visualizes the number of recognized letters by both raters in the three sessions.

We observed consistent and significant handwriting improvement after using LightWrite. Repeated measure ANOVAs and post-hoc pairwise t-tests with Bonferroni adjustment all showed significance ($p < 0.01$ between stage 0 and stage 1, $p < 0.001$ when comparing stage 2 with both stage 0 and stage 1). In the stage 0 session, participants could write an average of 0.9 recognizable letters (SD = 1.0). After the first day of learning, participants could write 7.6 letters (SD = 6.11), with an improvement of 6.7 letters on average; Moreover, after five more days of practice, the performance further improved by 12.3 letters and participants could write an average of 19.9 (SD = 5.8) out of 26 letters. To memorize the whole set of letters, more practicing is needed, as some participants reported to have forgotten how to write a few letters, and mismatches were found in the results. Figure 9 shows the improvement trace of the handwriting performance from participants. More writing samples generated in stage 2 can be found in the appendix.

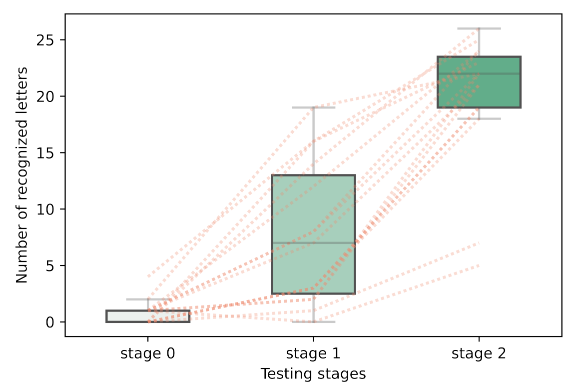


Figure 8: Box plot of the number of recognized letters recognized by both raters in three stages. Each participants' performance is indicated by the line plot overlaid. The participants' overall performance has improved significantly from stage 0 to stage 3, reaching an average of 19.9 letters in the final test.

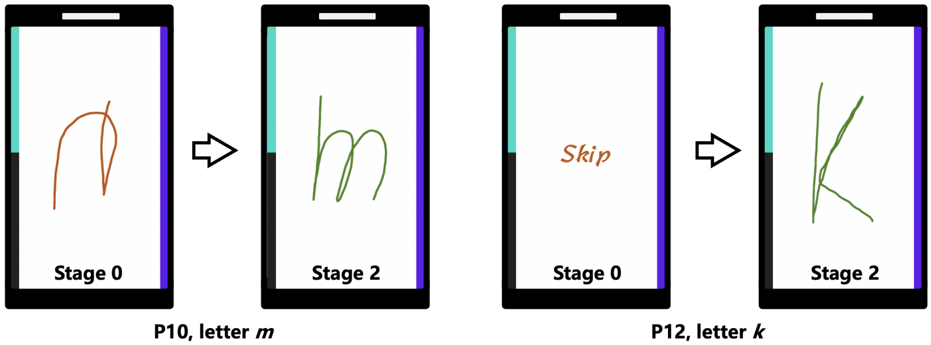


Figure 9: Two writing samples for stage 0 and 2 from two participants. P10 had the wrong idea of letter m in stage 0, but was able to write a correct one in stage 2. P12 skipped letter k in stage 0, which is the common situation for most letters for all participants. In stage 2, P12 was able to write k correctly.

During the interview, we first asked the participants to conclude their daily training process. All participants reported using the learning module together with the practicing module and/or testing module to learn handwriting. The results of the short questionnaire indicated that both modules were considered helpful in remembering the letters (practicing mode: mean=6.3 ± 1.0; testing mode: mean=6.7 ± 0.6). Moreover, participants were happy to recommend LightWrite to other BLV users (mean=6.4 ± 1.0). Although not even asked by the experimenter, two participants expressed their strong interests in continuing to use LightWrite after the study. Three participants reported having some kind of frustration when they were writing a letter wrong repeatedly, mostly with letters that contain arcs.

Our interview results also indicated that learning handwriting on a smartphone could potentially be beneficial in more general cases. When asked at the end of the interview if there were anything they would like to add, P6 and P12 reported that they tried using pen and paper to write some letters and the handwriting was successfully recognized by their family members. P6 (right-handed) used the left hand when using LightWrite because it is how they usually operate with the phone, but could still write with the right hand when trying with pens and papers. Moreover, P2 and P3 proposed that the system could be useful in teaching more complicated geometrical shapes, such as the degrees of an angle.

6 DISCUSSION

In this section, we first discuss the potential implications of our studies, and then discuss the possibility of improving LightWrite with crowdsourcing and extending LightWrite to other teaching scenarios. We also discuss potential applications based on LightWrite. Finally, we reflect on the limitations of our work.

6.1 Understanding Graphics from Verbal Description for BLV Users

Different from previous attempts of training hand movements directly[24, 41], we adopted voiced description as the main input for understanding graphic information. During the study, we discovered that most participants could only imagine the shape of a character after having finished the character for once, instead of processing the information provided. This could be because the cognitive load and the capacity of working memory limit the ability to remember previously processed stroke parts and processing the new instructions given at the same time. We also discovered that although some participants claimed that they have understood a shape, they could not produce the shape correctly without training or assistance. The conflicted behavior could be because of the incorrect belief of the shape described, or because the motor skills are limited because no visually real-time feedback on the current handwriting is available. These findings are valuable for us to further understand the process of understanding, imagining, and producing graphics for BLV users. However, as it is not closely inspected in our work, we could only provide some hypotheses on what we have observed. A further study focusing on the mental model of the process could be conducted to investigate the underlying mechanism during the process.

6.2 Crowdsourcing for Handwrite Teaching

In the character learning module, LightWrite leverages machine learning models and the rule-based algorithm to provide intelligent feedback and suggestions on the handwriting results. However, due to the unpredictability of human writing error, cases where CNN models and the rule set could not recognize the writing or produce wrong outcomes are inevitable. Crowdsourcing could be an effective way to combine human intelligence and machine intelligence to help BLV users to learn handwriting [11, 12]. Slighted volunteers can participate in the process of providing personalized feedback for writing results. As the feedback accumulates, LightWrite can also leverage it by online learning techniques to further improve its algorithm [14]. Moreover, a community can also be built using crowdsourcing to help connect the visually impaired and the sighted population, form a mutual bond during the process, and provide social support during the learning process.

6.3 Extending LightWrite for Learning Writing in General

Although LightWrite is designed based on the goal of teaching English lowercase letters and Arabic numerals, it is easy to extend its teaching capacity to other languages, especially those with limited characters, such as Indo-European languages and Latin language family [22]. However, additional care in design would be needed before applying LightWrite to languages with a large set of characters such as Chinese and Japanese, or characters with complex geometric structures such as Korean. Without haptic guidance, like pulling the user's hand around a predefined trajectory [13, 47], it remains an open problem on how to leverage the modalities available on smartphones for complex language handwriting.

While LightWrite was designed to be used with finger input on a smartphone, writing with a stylus or a pen is more common in practice. In the current design, LightWrite only provides graphical information of the letters. For users to learn writing with other mediums, additional training on motion control of the stylus is needed, and feedback should also be adjusted based on the medium used. As discovered in our evaluation study, two participants reported having the potential to transfer the graphical knowledge obtained from LightWrite to other mediums, *e.g.*, writing letters with a pen on a piece of paper, provided that they already have the knowledge of using pens. This indicates that the teaching method of LightWrite – the font design, voice instructions, and feedback – has the potential to assist teaching writing with other mediums by providing the information on the shape and adjusted stroke orders.

It is worth mentioning that handwriting words and sentences is different from writing single characters repeatedly. To write a complete sentence or word, spacing and arranging all characters on a straight line is of concern. As the writing space is limited on a smartphone, additional training on the relative positions of characters in a sentence is needed for BLV users to produce complete writings.

6.4 Beyond Handwriting

The process of teaching handwriting to BLV users is essentially a process of teaching the drawing of a graphic symbol set. Therefore, the design implications and the findings of the handwriting learning process can potentially be extended to other situations where BLV users need to understand and write shapes, *e.g.*, learning a new set of interaction gestures, or understanding artistic graphics with abstract shapes. As LightWrite is based on descriptive instructions and vibration feedback that a smart device can easily provide, our teaching method is compatible with a wide range of existing electronic products. Any application on these devices can include a built-in gesture learning module for BLV users to learn gestures, provide an additional interaction channel beyond the screen reader, and improve their user experience in the application.

6.5 Potential Applications

With a low-cost system that can be easily acquired, LightWrite provides another way for BLV users to communicate with the sighted population, and bridges the gap of handwritten language between them and their sighted counterparts to some extent. More applications could also be supported as a by-product of LightWrite. We developed two demo applications for illustration. The first is handwriting text entry software, which translates the handwritten characters to inputs, thus frees the audio channel that BLV users usually rely on during the ordinary text entry process. This could also help mitigate privacy issues when users are trying to input passwords, approve transactions, and enter other sensitive information, as the input process does not require users to play it out loud. The second is a shortcut application selector based on the handwriting inputs. Because handwriting can be considered as a type of gesture with linguistic information, it can be used as another complement to the current gesture set commonly used by BLV people. We developed a shortcut menu that presents all applications starting with the letter written by users. To further extend the application, other designs such as customizing some letters to trigger a specific application or a set of pre-recorded interactions could also be applied.

6.6 Limitations and Future Work

There are a few limitations to our work. First, although the system is designed to teach English letters and digits that are universal, it was evaluated with participants who learned English as a second language. We plan to conduct another user study with English native BLV users to validate our system design. Second, our CNN models still have room for improvement. The recognition accuracy can further be improved by wider data collection, better data augmentation techniques, and more advanced network structures. Moreover, we also plan to add another category of unrecognizable characters to deal with bad writing cases. Third, the current version LightWrite only supports teaching a single character for lowercase English letters and digits. It does not involve teaching the relative position and space between multiple characters, thus does not provide sufficient training for writing complete words or sentences. In the future, we plan to further design the font of uppercase letters, and add a word learning module after the character learning module to support word handwrite teaching.

7 CONCLUSION

Existing solutions for teaching handwriting to BLV users are still very costly. In this work, we propose LightWrite, a low-cost, easy-to-access system that aims at teaching the handwriting of 26 lowercase English letters and 10 Arabic numerals to BLV users using only a smartphone. Based on a pilot study with BLV users (N=6), we designed a new type of font that is easy for BLV users to understand and memorize, as well as a voice-based teaching method to describe the font. We then conducted a formative study with six BLV participants to obtain a set of design implications and implemented LightWrite. Our system consists of five modules, including basic stroke training, character learning, practicing, testing, and free-writing, and allows users to leverage these modules according to their own learning pace. We conducted a two-stage longitudinal evaluation study in seven days with another 15 BLV users. Our results showed that participants could successfully write out an average of 19.9 out of 26 letters after an initial training stage and a five-day practicing stage (only 20 minutes per day). Moreover, LightWrite received very positive feedback from participants. Our work demonstrates how the smartphone can be used for handwriting teaching and we hope to see other researchers leveraging smartphones and other commercial devices to provide more teaching assistance for BLV users.

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A SAMPLE WRITING FROM STAGE 2

In this section, we present 20 sample writings generated by 15 participants from stage 2.

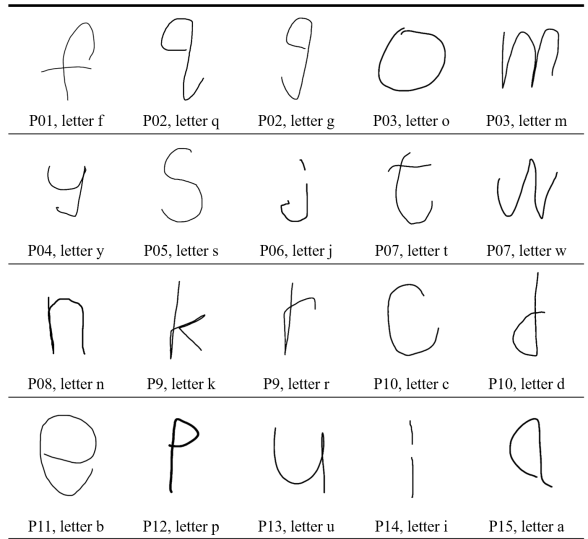

Figure 10: Twenty sample writings from 15 participants generated from stage 2. Although the writing styles for each participant differ slightly, all letters are recognizable by both sighted raters.