AccessibleCircuits: Adaptive Add-On Circuit Components for People with Blindness or Low Vision

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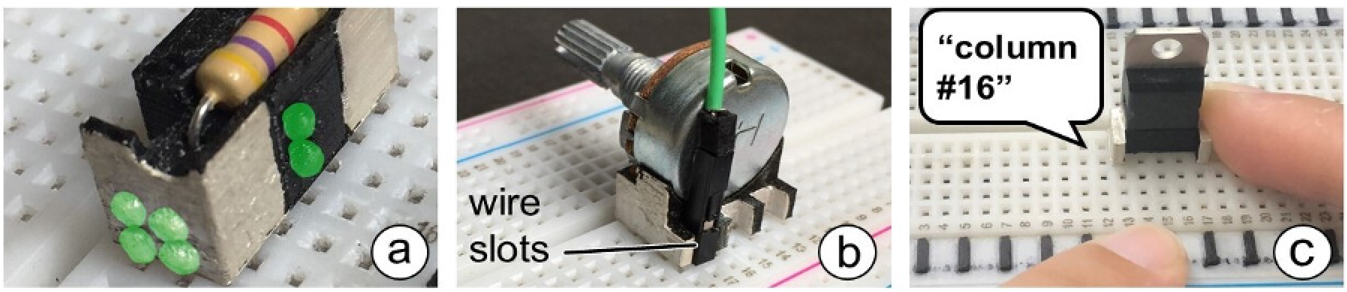

Figure 1: AccessibleCircuits system. (a) Braille text describing the value of a resistor's color stripes; (b) 3D printed add-on adaptations for potentiometer with wire slots; (c) User touching the component add-on to trigger audio feedback.

ABSTRACT

In this paper, we propose the designs for low cost and 3D-printable add-on components to adapt existing breadboards, circuit components and electronics tools for blind or low vision (BLV) users. Through an initial user study, we identified several barriers to entry for beginners with BLV in electronics and circuit prototyping. These barriers guided the design and development of our add-on components. We focused on developing adaptations that provide additional information about the specific component pins and breadboard holes, modify tools to make them easier to use for users with BLV, and expand non-visual feedback (e.g., audio, tactile) for tasks that require vision. Through a second user study, we demonstrated that our adaptations can effectively overcome the accessibility barriers in breadboard circuit prototyping for users with BLV.

CCS CONCEPTS

• **Human-centered computing → Accessibility systems and tools**.

KEYWORDS

Tangible User Interfaces; Universal Design; Accessibility; Circuit Prototyping; Education Tools

ACM Reference Format:
Ruei-Che Chang, Wen-Ping Wang, Chi-Huan Chiang, Te-Yen Wu, Zheer Xu, Justin Luo, Bing-Yu Chen, and Xing-Dong Yang. 2021. AccessibleCircuits: Adaptive Add-On Circuit Components for People with Blindness or Low Vision. In *CHI Conference on Human Factors in Computing Systems (CHI '21), May 8–13, 2021, Yokohama, Japan.* ACM, New York, NY, USA, 14 pages. https://doi.org/10.1145/3411764.3445690

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CHI '21, May 8–13, 2021, Yokohama, Japan

ACM ISBN 978-1-4503-8096-6/21/05…$15.00
https://doi.org/10.1145/3411764.3445690

1 INTRODUCTION

In the maker community, beginners use circuits and breadboards to create electronic prototypes. However, circuit prototyping is extremely challenging for people who are blind or low vision (BLV), since much of the prototyping environment (e.g., circuit components, breadboards, and micro-controller devices like Arduino) relies on visual information that is barely accessible to the BLV community [13]. The high entry barrier to learning electronics also excludes the BLV community from crucial STEM education and later in high-technology careers [11] since learning electronics is an essential gateway to many engineering and science disciplines in higher education. While efforts have been made to address some of the accessibility barriers in electronics and circuits, the existing work primarily focuses on learning materials [13]. Circuits prototyping with a breadboard is still largely inaccessible to the BLV community.

To overcome this challenge, we took a user-centered design approach. We first investigated the accessibility barriers in the existing circuit prototyping environment through a user study with 10 self-reported blind participants. In this user study, we evaluated the accessibility of common electronic components used by beginners and important tasks needed to successfully construct breadboard circuits, such as inserting a component into a breadboard, connecting breadboard components using wires, and stripping wires. Our results suggested that participants could identify the tested components through touch without any significant issues. However, we observed major accessibility barriers in the participants' interactions with the breadboard and tools, including the probes and wire strippers. The most significant challenge was identifying the correct hole on the breadboard to connect the components and wires. There was also a lack of audio or tactile feedback in the breadboard regarding where a component was inserted. While participants could navigate the breadboard by counting rows and columns, this method was very slow and error prone.

To overcome the key accessibility issues identified in our study, we designed and developed low-cost, 3D printable, add-on adaptations for the components, breadboards, and tools. Our adaptations were designed as component wrappers or extensions with accessible features, such as Braille or tactile labels. For example, our resistor adaptation includes Braille text describing the value of its color stripes (Figure 1a). We created adaptations with conductive filament that can be used with a touchscreen device (e.g., a smartphone) affixed to the breadboard. These adaptations then allow for touch-based interactions that respond to a user's input and notify them about the information needed to create a circuit (e.g., the location of an inserted component). For example, when a user touches a pin (or leg) of an inserted component, the smartphone plays audio feedback, detailing which column the pin is located (Figure 1c) since breadboard holes on the same column are electrically connected. The adaptations were also designed to provide haptic landmarks to help users connect jumper wires to the desired pins (Figure 1b). Through a user study, we demonstrated that our adaptations and interactive system could significantly address the accessible barriers in the existing circuit prototyping environment. With our system, participants were able to construct breadboard circuits more accurately and quickly.

The main contributions of this work are: (1) an understanding of the accessibility barriers in the existing circuit prototyping environment for users with BLV through an initial user study; (2) an approach to address these issues by using interactive tactile adaptations for circuit components, breadboards, and tools; (3) the results from a second user study, demonstrating the effectiveness of our accessible circuit prototyping environment.

2 RELATED WORK

Our research builds on the existing work in electronics learning materials and circuit prototyping tools.

2.1 Learning Electronics in Making and STEM Education

Electronics is an important part of STEM education and a gateway to many science and engineering fields in higher education. As shown recently through the success of physical computing [21], learning STEM subjects like Computer Science, Engineering, Biology, Physics, or Mathematics [23, 36, 50] is more engaging for students when they develop hardware interactive systems through electronics, sensors, and actuators [26, 39]. In CS, for example, electronics has been used in physical computing to teach a variety of topics, including programming, computational thinking, data structure, and digital logic [23, 40, 48, 50, 58]. Students report that learning through building interactive circuits leads to a much more positive experience than a traditional screen-based experience because the computational concepts are presented in the real world [8, 20, 26, 27, 30, 40, 41, 58].

Efforts have been made in designing computer programming for users with BLV [9, 35, 49, 55, 56]. For example, accessible programming languages (i.e. Quorum) and speech interfaces (i.e. Emacspeakiv) have been created to empower programmers with BLV. To assist students who are BLV and learning to program, Smith et al. [55] introduced JavaSpeak to provide information about the structure and semantics of written Java code. These approaches mostly serve to increase the accessibility of text-based programming without using physical objects for learning complicated concepts [52] or for supporting collaborative learning [24].

Low-cost 3D printing has been used in education before. A recent work from Li et al. uses tactile line drawings combined with audio feedback to aid people with BLV in understanding the spatial information of a web-page layout [31]. Other work demonstrates potential usefulness of 3D printed models as learning tools for users with BLV [51, 53, 54]. In contrast, little research has been conducted to explore the effectiveness of tangible modalities within the realm of electronics. Historically, circuit diagrams are described using accessibility text through a screen reader [4]. However, a study shows that novice users found it very hard to understand the spatial and structural information of the circuits [43]. Race et al. [42] used swell paper (raised line drawings on paper that are felt by hand) to render circuit schematics but this approach fails to connect the user between high-level concepts and the actual implementations on the breadboard [43]. TangibleCircuits [13] overcomes this challenge through an interactive tutorial system using a 3D printed tactile model of a breadboard circuit. When a component is touched, the system plays audio feedback detailing the name of the component, the position, and other implementation details. The authors showed that BLV users were better able to recognize the geometric, spatial, and structural information of circuit diagrams using TangibleCircuits than using the existing tutorials modified to be BLV accessible according to WCAG [5]. This work shows the effectiveness of using low-cost 3D printing and audio feedback to create accessible circuit learning materials. However, constructing breadboard circuits is still largely inaccessible for people with BLV. In response, our work primarily investigated the accessibility challenges in users' interactions with a physical breadboard, components and tools widely-used such as probes and wire stripper. Our contributions include the design, implementation, and evaluation of 3D printable adaptations to make the construction of circuits more accessible.

2.2 Tools for Prototyping Electronic Circuits

Creating electronic circuits can be difficult for beginners. Many tools have been created to make it easier for users to create hardware electronic devices, including modularized circuit components [14, 29], morphed circuits on different appliances [22, 28, 32, 44, 45, 65, 66], novel prototyping platforms [60–63] and software systems that can generate circuits through high-level inputs [7, 18, 19, 25, 33]. Specifically, Programmable Bricks [47] allows children to develop interactive devices using PINO bricks embedded with sensors and actuators. Tools like PICL [16] allow users to create sensor-based interactive devices using "programming by demonstration". Although these tools are in general easy to use, their applications are limited to a small number of existing modules. In contrast, open-source hardware platforms (e.g., Arduino [3], Phidgets [17], or Microsoft .NET Gadgeteer [59]) are more flexible and thus prevalent in the maker community and electronics education. With easy-to-use microcontroller devices, users have the freedom to design and create their own electronics projects. Additionally, circuits are prone to errors [10, 38], which can appear in either software or hardware, becoming a major source of frustration especially for novice users [38]. Commercially available tools like Digilent Electronics Explorer [1] augment breadboards with common debugging tools (e.g., oscilloscope, pattern generators), but require users to have some background in electronics to use them effectively. Research projects like Toastboard [15], Bifrost [37], and Scanalog [57] lower this barrier by providing solutions that are easier to use for novice users. While varying types of tools exist for sighted people, little research has been conducted to investigate the accessibility barriers in circuit prototyping by people with BLV.

3 STUDY 1: UNDERSTANDING THE ACCESSIBILITY OF CIRCUIT PROTOTYPING ENVIRONMENT

To understand the accessibility barriers in the existing circuit prototyping environment, we conducted a user study with people with BLV. We were interested in investigating whether they could perform some of the most common tasks in circuit prototyping, such as identifying components, constructing breadboard circuits, understanding constructed circuits, probing, and stripping a wire.

3.1 Participants

Ten self-reported blind participants (6 male and 4 female) with no electronics educational backgrounds were recruited through the assistance from a local organization serving the BLV community. Having background knowledge or not does not affect our study since our focus is on how accurate users with BLV can perceive circuits through touch. Participants ranged in age between 20 and 30 (median age: 26.5), and eight of the participants were born blind.

3.2 Apparatus

We wanted to include some of the most common circuit components used by beginners. To identify the components for the study, we first randomly sampled 500 circuits developed on a half-sized breadboard from Fritzing Projects [2], an open-source online community for sharing circuit projects common among beginner circuit builders. Among the 31 types of components found in these circuits, we chose the ones appearing 10 times or more. We then removed the output components that require vision to use (e.g., LEDs), as well as the ones that are uncommon in introductory level electronics projects (e.g., Capacitors). Among the ICs with varying number of pins, we opted for the one with 16 pins. Figure 2 shows the final list of the 12 components evaluated in the study. Aside from the components, study apparatus also included a breadboard, a wire stripper (Pro'sKit 8PK-3001D), and a set of probes, which are essential and widely-used tools for circuit building.

3.3 Tasks and Procedure

Our study involved a learning and a testing session.

3.3.1 Learning session. In the learning session, participants were introduced to the tested components, breadboard, probes, and wire strippers. We explained the name of the components and tools and demonstrated the general use of them. We also taught participants how to identify the pins of the components. For example, the base pin (pin_1 for simplicity) of a transistor is the leftmost pin when the metal side is facing the user (Figure 4a). The pin_1 of the IC can be found at the bottom left corner of the clip, identifiable through the polarity marker (a half-moon shaped dent). We then asked participants to feel and identify the components, construct a simple breadboard circuit, explore the circuit, and operate the probes and wire strippers. The learning session ended once participants felt they had a reasonable understanding of the components and tools.

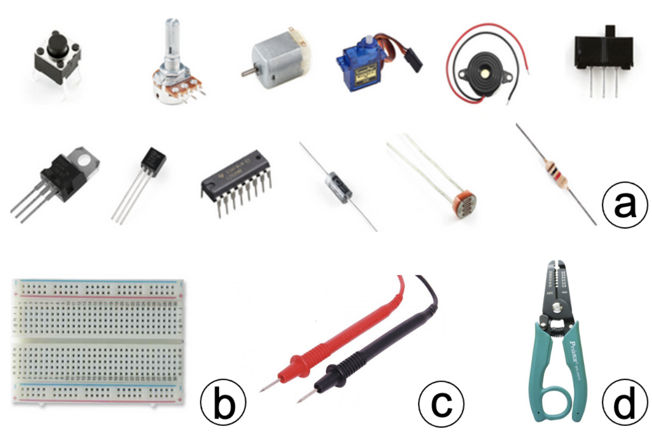

Figure 2: (a) Components include a button, potentiometer, motor, servo, buzzer, slide switch, transistor, temperature sensor, 16-pins IC, diode, photocell, resistor, (b) half-size breadboard, (c) probes, (d) and a wire stripper.

3.3.2 Testing session. For testing, we included five tasks that are common in circuit prototyping.

Task 1: Identifying components. Participants were asked to identify the 12 components presented to them in a random order.

Task 2: Inserting and connecting components. Participants were asked to insert a sub-set of the tested components into the breadboard and connect them using wires. From initial observations, we found that insertion is primarily affected by the physical property of component pins. For example, the ones with soft pins that are subject to bend (e.g., temperature sensor) are more difficult to insert than the ones with stiff pins (e.g., ICs). Many of the tested components share pin properties, so we chose four unique ones for this task: diode, temperature sensor, button, and 16-pin IC. The diode represents the components with two long pins (e.g., resistors), while the temperature sensor represents the components with multiple long pins (e.g., transistors). The button represents the components with multiple short soft pins, and the IC represents the components with multiple short stiff pins (e.g., potentiometer, slide switch). Additionally, we chose three common sizes of wires (0.2, 0.4, 0.6 mm), which includes the components with lead wires (e.g., servo, DC motor).

In each trial, participants were asked to insert a component into a randomly selected location on the breadboard. For the components with multiple pins (e.g., IC, transistor), pin_1 should be inserted into the target hole with the remaining pins falling into the neighboring holes naturally. For wires and the components with two pins (e.g., diode, resistor), each pin had to be inserted into a right hole. The IC and button were always placed between rows E and F, straddling the gap in the middle of the breadboard. Participants were asked to insert two components first and then connect them using one of the three wires picked randomly for the trial. The component pin for wire connection was also chosen randomly. This process repeated for all the three wires. Since we did not have components for the last wire, we randomly chose two for participants to connect.

Task 3: Understanding an existing circuit. In circuit prototyping, it is a common skill to understand existing circuits created by others or themselves. To understand the accessibility of this task, we presented two breadboard circuits to our participants, who were asked to identify the components in the circuits and describe how they were connected (e.g., through which pin). Participants were also asked to identify the location of the components and wires (e.g., the coordinates of the breadboard hole where the component/wire were inserted). In addition to the components and wires from Task 2, we included the potentiometer and slide switch to better understand how different component form factors may affect the user's ability to perceive the location and wiring. The tested components were randomly assigned to the two circuits (Figure 3). The circuits were not electrically functional, and our goal was to understand how well the connections and locations of circuits could be perceived through touch.

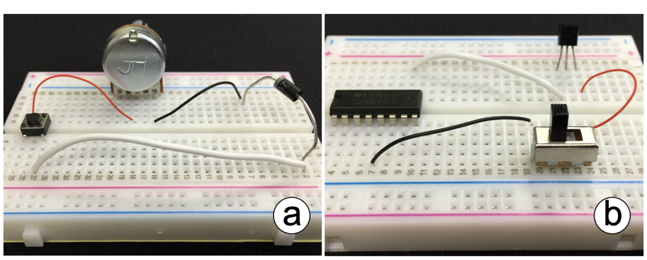

Figure 3: Tested circuits in Task 3 (a) with a button, potentiometer, diode, and three wires, (b) with a slide switch, IC, temperature sensor, and three wires.

Task 4: Stripping wires. We gave participants three tested wires with each one stripped on one end. Participants were asked to identify the unstriped end and remove the insulation using the wire strippers. We told participants the position of the corresponding stripping blade slot for each wire (e.g., the slot for the thinnest wire is the first one near the tip of the wire strippers), but they had to find it in the study by themselves.

Task 5: Probing. Probing is a common task involved in tools like an oscilloscope, multimeter, or signal generator. Our aim of this task is to explore how accurate participants can probe on the assigned pins, not to operate the machines or read the output. Participants were asked to probe the components without auditory feedback. This task required them to simultaneously touch two pins on a component using the tip of the probes. The same set of components and wires were chosen for this task, and the pins were randomly chosen. The order in which the components were presented was also randomized.

During the study, each participant completed the learning session (two hours) a day before the testing sessions, which began with a demographic experience questionnaire, followed by a 30 minutes warmup for participants to go over what had been learned. During the testing session, participants performed the five tasks in a fixed order. They were asked to perform the task as quickly and accurately as possible.

3.4 Dependent Measures

Given the tangible nature of circuit prototyping, we expect that the participants could complete the tasks sufficiently without vision if they had enough time or training. However, for novice learners, spending too much time and effort on routine tasks will take away their attention from more important ones, such as learning or designing circuits. Therefore, we restricted the time that participants had for each step of the study. If a step was completed within the time threshold and without error, it was marked as success. Otherwise, it was marked as incomplete.

The time threshold for each step of the tasks was determined based on the task completion time of a blind hardware engineer (see tables in appendix), who manages a computer lab for the organization, where we recruited our study participants. The engineer had no previous experience in breadboards and circuits but was very familiar with wires and computer parts. We ran our study with the engineer, and for each step, we recorded the time from when the task began to the time when the engineer felt it was completed despite the occurrence of errors. We expected that most beginner learners might be slower, so we doubled the times for our thresholds. The reason that we adopted this time threshold is to avoid fatigue for our participants (similar protocols can be found in prior research [34, 46]).

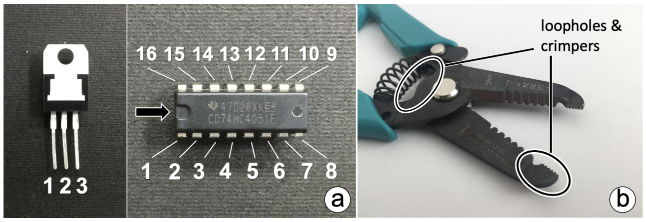

Figure 4: (a) Illustration of component pins. (b)Any loopholes and crimpers can mislead participants.

3.5 Findings

In this section, we report our findings from the first study.

3.5.1 Identifying Components, Their Value or Polarity. Participants were able to complete all the tasks within the time threshold. They could recognize and describe the name of the components correctly in 85.8% of the trials. For another 10.8% of the trials, participants told us that they recognized the shape of the components but was unable to recall their name. In the remaining 3.3% of the trials, participants recognized the components incorrectly. For the trials completed within the time threshold, it took an average of 2.38s (SD = 0.44) for participants to identify a component or wire.

Participants recognized the components primarily based on shape, number of pins, and how they could be manipulated (**G1**). Even subtle haptic cues played an important role in recognition, like when participants used the small bumps on the resistor to distinguish it from the diode. Participants also distinguished the components based on the number of pins. For example, when P2 forgot the name of the temperature sensor, the participant told us that "it has three pins, and I know it is not a transistor". Furthermore, the moving parts of the components also served as important clues—participants recognized the button as something that can be pressed and that a potentiometer or servo motor was recognized as something that can be rotated. A participant said *"I can rotate it to distinguish between potentiometer and servo, as a second confirmation beyond the shape"* (P9). However, these clues from the physical form of the component also sometimes misled participants. Errors in identification occurred when components were similar in shape or the way they can be manipulated like when the photocell was confused with the temperature sensor due to the similarity of the shape of their cores.

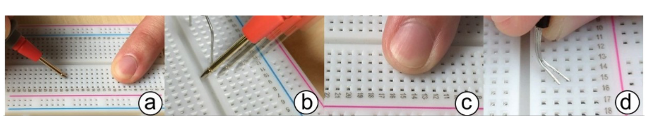

Figure 5: (a) Most participants used their dominant hand to probe and non-dominant hand to hold the breadboard in place. (b) The probe tip slipped off to the middle gap of breadboard. (c) "Fat finger" makes the pointing tasks hard, especially when using the thin wires. (d) The pin of the temperature sensor was deformed when counting.

The result of this part of the study is highly encouraging as most of the tested components could be correctly recognized through touch. However, components may have a value (e.g., resistor) or polarity (e.g., diode, motors, buzzer) that rely on vision to determine, like reading the color strips of a resistor or identifying the polarity of components using color. Even though some of the components have haptic markers to distinguish value or polarity, many do not, (e.g. IC's that do not have dents to mark polarity) which lead to accessibility issues.

3.5.2 Inserting and Connecting Components. Among all the trials that required inserting a component, 20% were successful (e.g., components inserted into the target location within the time threshold). Among all the trials that required wiring, 23.3% were successful (e.g. both ends inserted in the target component pin within the time threshold). To navigate the breadboard, participants counted the holes using rows and columns. Most of them (80%) used a probe to count, and the rest used their pointer finger. They used their dominant hand to count using the probe or finger, and the non-dominant hand to hold the breadboard in place on the table (Figure 5a). The entire process required participants to coordinate between both hands and was error prone. For example, when counting, the probe tip often slipped off the desired row or column (Figure 5b) (**G4**, **G7**). Using a fingertip often resulted in the classic "fat finger" problem, as a finger was too big to accurately point at the holes (Figure 5c) (**G3**, **G7**). Furthermore, when the probe tip was removed from the target hole, participants lost the reference to the target (**G4**, **G7**). P1 used a component pin to count. It worked well for the IC, but for the other components (e.g., temperature sensor, button), the pins were too soft to stand the push against the breadboard when pointing and counting (Figure 5d) (**G2**). When the pin was bent, participants needed to fix the pin with both hands, which meant participants picked up their finger pointing at the target location on the breadboard. This often led to the entire process needing to be restarted.

Participants used the haptic landmarks on the breadboard to aid their search of target holes. For example, P8 used the gap in the middle of the breadboard to quickly locate row E and F. However, the landmarks also caused confusion in some scenarios. When P4 inserted the button, they inserted two pins on row E with the other ones landed inside the groove instead of the correct holes. (Figure 6a). Furthermore, the participant did not notice the error even when they double-checked whether the button was inserted properly. When inserting a component with short pins (e.g., button), there was not enough haptic feedback provided by the spring clip inside the holes to indicate that the component was firmly connected (**G7**), and many participants often asked if we could confirm for them. For the components with thin pins that are near each other (e.g., temperature sensor), it was a common mistake for participants to insert both pins into the same hole (Figure 6b) (**G2**).

When wiring, participants first located the target pin on a component (using either probe or fingertip), and then inserted a wire into the same column on the breadboard. A number of accessibility issues were observed during this step. First, when a component was on the breadboard, salient haptic features were largely missing for the pins and hard to feel using the probe tip or a fingertip (Figure 6c) (**G2**). Second, the pins of some components (e.g., potentiometer)

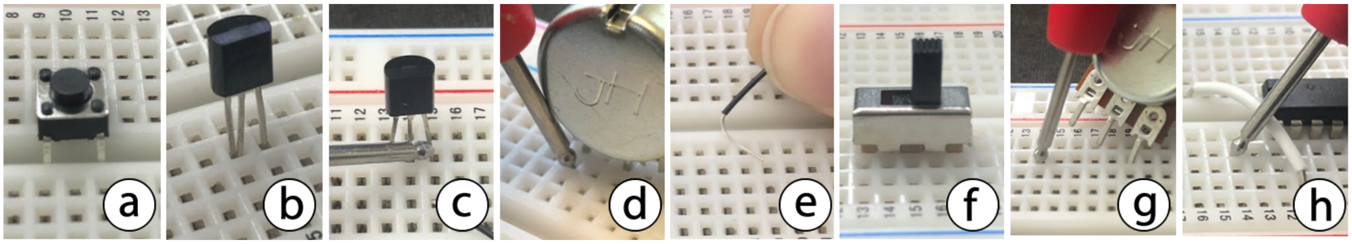

Figure 6: (a) P4 inserted the button cross the groove of the breadboard and confidently thought it was completed. (b) P1 inserted two pins of temperature sensor into the same hole. (c) The pins of temperature sensor are too thin to be felt by probe. (d) The pins of potentiometer are occluded by the body. (e) The end of wires is easily bent. (f) The pins of the slide switch are hidden. (g) Component bumped off the breadboard. (h) Wires can hinder the movement of probe.

were occluded by the component body, making them inaccessible through touch (Figure 6d) (**G3**). These led to the comment by one participant: *"It was hard to confirm whether a wire was inserted into the same column as the target component pin"* (P6). Third, the end of the wires, especially the thin ones, bent easily when they were (mistakenly) pushed against the surface of the breadboard outside a hole (Figure 6e) (**G2**). When the head was bent, participants needed to fix the pin with both hands, which required extra time and effort. As one may expect, these findings could also provide insights into the accessibility of Arduino boards.

3.5.3 Understanding Existing Circuits. Participants were able to identify the components on the breadboard, but no one was able to figure out how the components were connected within the circuits or their location. Among all the components and wires involved in this task, participants were only able to correctly describe 25% of them regarding location and wiring.

The issues described in Figure 6a-e were also common in this task. Additionally, for the components new to this task, we found that the pins of the slide switch were completely hidden inside the breadboard (Figure 6f), making them inaccessible through touch (**G3**). Thus, participants had to guess their location. A participant reported that *"I guess the location of pins based on the length of switch"* (P8). When exploring the circuits, participants often accidentally bumped a component or wire off the breadboard (Figure 6g) (**G4**). Without knowing their original location of the component or wire, participants were unable to put them back. Counting the row/column coordinate of a component was also difficult within a circuit when the path was blocked by another component or wire (Figure 6h) (**G4**). The wires of different sizes were also hard to distinguish when laid flat on the breadboard.

3.5.4 Stripping wires. Participants were able to find the unstriped end of the wires, but they were only able to successfully strip the wires for 43% of the trials. The success rate for the 0.2mm, 0.4mm, and 0.6mm wires are 30%, 50%, 50% respectively. Thinner wires were harder to strip. We observed several accessibility barriers. First, the loopholes and crimpers were often confused with the stripping blade slots (Figure 4b). Second, locating the correct stripping blade slot to match the thickness of the wire was hard, especially for the thin wire because it was difficult to feel where the wire was (**G5**). Third, the wires, especially the thin one, were hard to keep inside a stripping blade slot. When a wire slipped away from the gauge, participants had to put it back, which often required them to search again for the right slot (**G6**). A participant said *"It's difficult to locate the target blade slot. Additionally, though I found one, the wire was prone to slip off when I tried to push it hard into the blade slot"* (P8).

3.5.5 Probing. The overall success rate for probing was 42% The success rate for probing the temperature sensor, button, IC, diode, and potentiometer is 20%, 30%, 40%, 70%, and 50% respectively. The issues shown in Figure 6 were also common in this task. Additionally, wires were sometimes confused with the components with long pins (e.g., diode, resistor), and participants then probed the wrong components. Another common issue was that the components with thin pins (e.g., diode, resistor) were very hard to point at and probe (**G3**), as stated by P2 *"It was hard to hold the probe tip in place against a pin, as well as to confirm if the probe tip had correctly touched the target pin"* when he was probing on the temperature sensor.

3.5.6 Design Guidelines for Accessible Adaptations. Based on our study result, we propose a number of design guidelines for creating accessible adaptations to facilitate circuit prototyping for people with BLV.

G1. Preserve the accessible features that already exist in the current components, breadboards, and tools (shape, number of pins, moving parts, polarity markers).
G2. Avoid soft, short, or thin pins.
G3. Provide a mechanism to allow component pins to be accessible through touch or probe tip.
G4. Provide easy access to location information on the breadboard.
G5. On wire strippers, provide a mechanism to make the stripping blade slot of different sizes easy to search.
G6. On wire strippers, provide a mechanism to avoid the wires from slipping away from a stripping blade slot.
G7. Provide non-visual feedback (e.g., audio, tactile) for the tasks requiring vision.

4 ADAPTATION DESIGN AND IMPLEMENTATION

Following the guidelines in Section 3.5.6, we created a low-cost and scalable interactive tool to overcome the identified barriers. We wanted to develop an environment that can be independently used by both BLV and sighted people. Therefore, we aimed to only

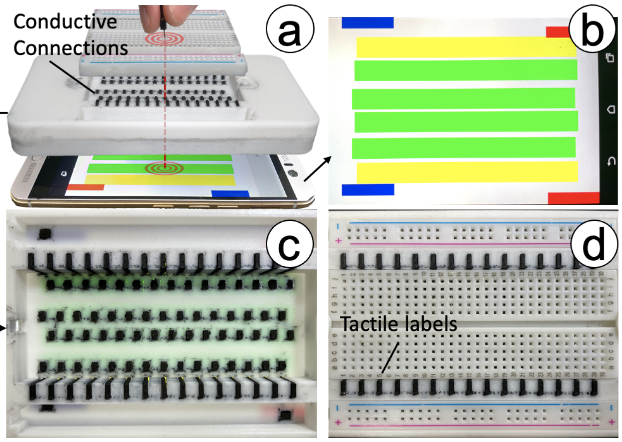

Figure 7: (a) AccessibleCircuits audio-haptic interface displayed on a commodity smartphone overlaid with the 3D printed adaptation (b) Smartphone interface. (c)Top-view of extension case. Each black squares is printed in conductive filament.(d) Encased breadboard and tactile labels.

make changes that could be adopted by using existing circuit components, devices, and tools. To do so, we designed and implemented a number of add-on adaptations using the technologies that are easily available to the BLV community, such as smartphones and 3D printing. Blind people were involved in our iterative design process to give us feedback on our design choices. We envision that proposed add-on adaptations can be fabricated and attached to the components and tools by sighted people, such as family, friends, or teachers of people with BLV.

4.1 Breadboard Adaptation

To provide location information on a breadboard (**G4**), we created an extension case, which has tactile labels that mark the odd columns of the breadboard (Figure 7b). Our initial design had labels for all the columns, but we found people with BLV were unable to separate them apart from each other using touch. The tactile labels are 0.9mm high (also tested by people with BLV) and were printed using conductive filament (Proto-pasta CDP12805). We placed the labels between the main body of the breadboard and power rails to allow easy access to the holes in the main body. We did not provide labels for the rows for simplicity's sake.

Aside from the labels, we also created a mechanism to provide audio feedback for the user to acquire the location information of an inserted component through a smartphone affixed to the extension. We removed the double-sided tape on the backside of the breadboard to allow the bottom of the spring clips to have contact with the conductive connections created on the bottom of the extension case (Figure 7a). Each small-square connection comprises of conductive filament and fabrics (3.3mm x 1.7mm), big enough to trigger touch on smartphones. This establishes a connection between the pins of an inserted component and the touchscreen (same as [64]). When a pin is touched, the smartphone detects a touch event at the pin location. This allows us to provide

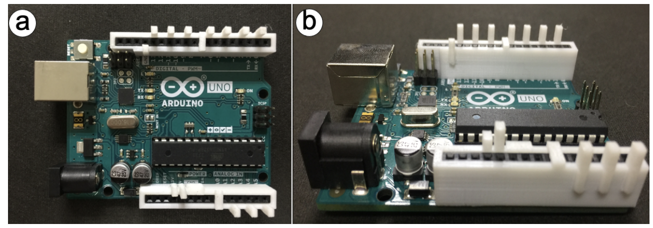

Figure 8: Adaptations with tactile labels for Arduino UNO.

vibrotactile feedback to indicate a firm connection and inform the user about the pin location using audio output.

The haptic-audio interface consists of six rows as touch listeners, which align with the layouts of tactile labels (yellow) and spring clips of breadboard (green, Figure 7b). Each row is equally divided into 30 pieces that correspond to 30 columns of a breadboard. Four power rails were also redirected to the small-square conductive elements to ensure reliable connection to smartphone (four squares in the borders). This way, we can manage subtle interactions by identifying a single or multiple touchpoints. Specifically, the audio feedback of the column location is provided once the user simultaneously touches the pin of the component and the tactile label next to it. This helps avoid unnecessary audio output when the user is searching the assigned column by touching over the tactile labels or exploring the tactile features of components (e.g. wire slots and polarity).

4.2 Arduino Adaptations

We marked the odd pins on an Arduino UNO board using tactile labels placed on the side of the pin headers (Figure 8). Similar to the breadboard, the labels and holes can be made interactive to support touch interaction with audio output. We chose to leave them passive in our current implementation since the layout of the pins of the UNO board is relatively simple. We placed the tactile labels for the digital and analog pins on the outer side of the headers. The labels for the power pins were placed on the inner side. We used labels of different heights to differentiate between the 3.3v, 5v, and ground pins.

4.3 Component Adaptations

We created the adaptations to ensure that the component pins are hard to bend (**G2**) and easy to access through touch or using a probe tip (**G3**). We also carefully designed the adaptations so that they do not significantly change the salient haptic features of the components (**G1**). Most of our designs involve a base piece, which hosts a component and provides proxies to the component pins that are easily accessible to the user. The proxies are conductive and electrically connected to its corresponding pin (painted in silver in Figure 9). This allows for audio-based interactions through touch. The base pieces for different components vary in terms of the number of pins, ranging from none to as many as a component has. For each pin, we designed a wire slot to make it easier for the user to connect the pin with a jumper wire (Figure 1b). The pins of the base piece were created using male jumper headers (Figure 9a). Note that the conductive parts of the adaptations need to be

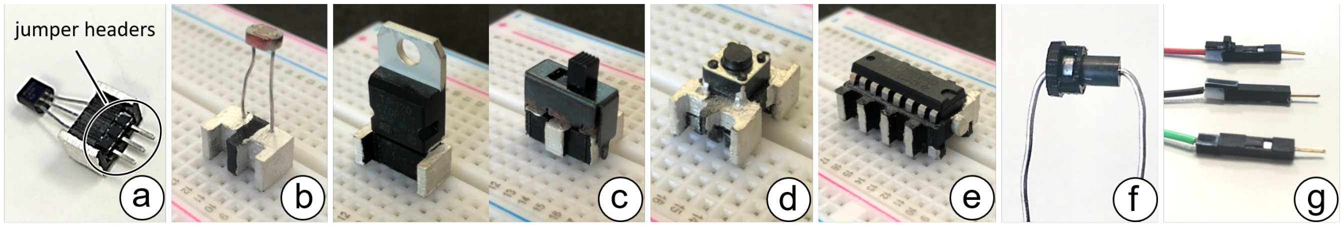

Figure 9: 3D printed add-ons for (a) temperature sensor, (b) photocell, (c) transistor and slide switch, (d) button, (e) IC, (f) diode, and (g) wires.

created using materials with low resistance in order for the finished circuit to function properly.

Resistor and Photocell. The design of the base piece for the resistor and photocell are similar. They both have two proxies, one for each pin, and wire slots that a jumper wire in the next hole on the column can fit into (Figure 1a, Figure 9b). These wire slots allow the user to easily find the right hole on the breadboard that connects to the desired component pin. To communicate the value of a resistor (**G7**), we show the color strip value haptically using Braille on the sidewalls of the base piece. We show the first digit, second digit, and multiplier on the left, right, and long side of the base piece (wire slots facing the user) (Figure 1a). We follow the Marburg Large Braille Font Standard [6] to ensure that the Braille text is printed large enough (e.g., point diameter 1.6mm, point height 0.9mm, the vertical and horizontal distance between points 2.7mm). We decided to not show the resistance value directly because reading color strips is part of the process for learning electronics.

Temperature sensor, slide switch, and transistor. The base piece has a similar design except that it has three pins instead of two. Because the pins of these components are near each other, the user may accidentally touch an adjacent pin if all the conductive parts are placed on the same side. Therefore, we put two proxies on one side and the middle one on the opposite side (Figure 9c). Since the pins of the transistor are already strong and insusceptible to being bent, we did not include pins for its base piece.

Potentiometer. The design of the base piece of the potentiometer is similar to that of the transistor except that the proxies and wire slots are all on the same side since the pin spacings are wider (Figure 1b).

Button. The design of the base piece for the button followed the same concept except that it has proxies at the four corners for each pin (Figure 9d).

IC. The pins of the ICs are located close together, so we only created wire slots for the even pins (Figure 9e). The odd ones are identifiable through touching the dividers of the slots. Unlike the other components, we only made pin_1 touch-sensitive for the sake of simplicity. The user can access the other pins by counting the tactile marks. We used a raised dot to mark the polarity of the IC (Figure 9e).

Diode. The adaptation for the diode is in the shape of a ring with a brim on one end (Figure 9f). The position of the brim matches that of the silver stripe on the diode to indicate polarity. We cut a hole in the ring to allow the silver stripe to be visible to sighted people. Since the pins of the diode are strong and insusceptible to being bent, we decided to not create a base piece for it.

Wires of the servo, DC motor, and buzzer. A dot on the header indicates the positive terminal (Figure 9g top). A long strip indicates the negative terminal, and a short strip indicates the control signal line (Figure 9g middle and bottom).

4.4 Wire Stripper Adaptation

Our adaptation for the wire stripper is composed of a wire guide residing on a slidable slot selector (Figure 10). The wire guide was made in a V-shape to allow easy placement of a wire into the desired blade slot. The guide was also made deep enough to prevent the wire from slipping off the stripper (**G6**). The slot selector was designed to help the user quickly locate the desired blade slot (**G5**). We used a multi-stage detent mechanism similar to the one on box cutters. The user can adjust the position of the wire guide by sliding the slot selector along the rail, and a click can be clearly felt when the selector is snapped into a slot.

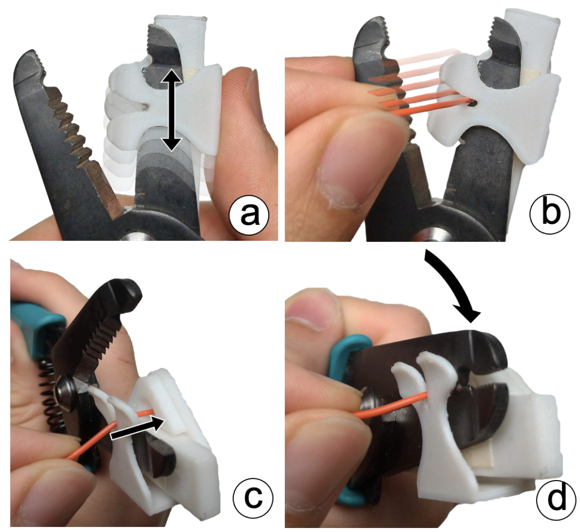

Figure 10: Illustration of the wire stripper adaptation. (a) Slidable blade slot selector. (b) V-shaped wire guide that holds a wire in the desired blade slot. (c - d) Users can move the wire and cut at a pre-set length.

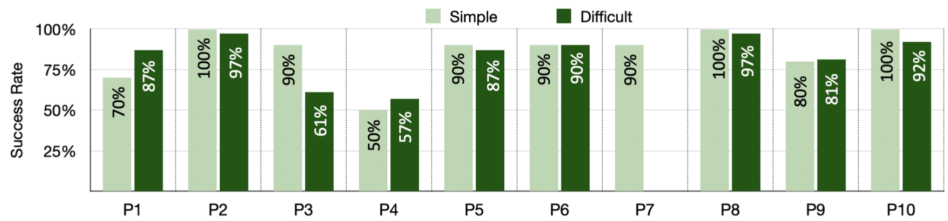

Figure 11: Success rate across participants of constructing the simple and complex circuits.

5 STUDY 2: EVALUATE ADAPTATIONS

The goal of this study was to measure whether and how well our add-on adaptations and interactive tools could overcome the most significant accessibility barriers identified in Study 1.

5.1 Participants and Apparatus

We invited the same group of ten participants from Study 1 to participate in this study. The apparatus remained the same except that the components, breadboard, and wire stripper were augmented using our adaptations and interactive tools. We also included the adapted Arduino UNO board in this study. The software of our audio-haptic system was implemented in Android, running on an HTC M9 smartphone.

5.2 Tasks and Procedure

During the experiment, participants were asked to perform the following tasks.

5.2.1 Task 1: Identifying components. In the component identification task, participants were asked to identify the components with add-on adaptations in a random order. To simulate the walk-up-and-use situation, we did not show participants the add-ons before the study.

5.2.2 Task 2: Circuit construction. After the identification task, we introduced our participants to the add-ons and interactive systems. Participants were then asked to use them to construct a simple and complex circuit by following step-by-step verbal instructions detailing the name of the components within the circuits, their location, and how the components were connected through the wires and the breadboard. The simple circuit involved a slide switch and resistor (Figure 12a) while the complex circuit involved more complicated components, such as an IC, DC motor, potentiometer, and button (Figure 12b). Both circuits are commonly learned by beginners. For the components with multiple pins (e.g., IC, slide switch), pin_1 should be inserted into the target hole. For the wires and components with two pins (e.g., resistor, DC motor), each pin had to be inserted into a right hole.

5.2.3 Task 3: Probing. Upon the completion of the circuit construction task, participants were asked to probe the components within the circuits. For each component, we randomly chose two pins as the targets. We did not include the DC motor in this task since it was connected through wires. We also removed the wires on the breadboard to avoid occluding the target pins. No audio feedback was provided since the barrel of the probes is not conductive.

5.2.4 Task 4: Stripping wires. Finally, in the wire stripping task, participants were asked to strip the wires of three different sizes (0.2, 0.4, 0.6 mm) using the adapted wire stripper.

Unlike Study 1, participants could take as long as they wanted to complete the tasks. Upon completion of the study, participants indicated subjective ratings for Easy-To-Use, Easy-To-Learn, Frustrating, Efforts, Confusion, and Confidence (1: 'not at all', 7: 'very much'). The experiment took around 2.5 hours.

5.3 Dependent Measures

We recorded Task Completion Time and Success Rate for each task. For all the tasks except the circuit construction, the success rate was calculated based on the number of successful trials per task. For the circuit construction task, the success rate was calculated based on the number of times a component or wire was correctly inserted into a target over the total number of targets.

5.4 Results and Discussion

In this section, we discuss the findings of the study.

5.4.1 Identifying Components . Overall, the success rate of component identification in the walk-up-and-use condition was 93% (SD = 6%). It took an average of around 5.91s for the participants to successfully identify a component or wire. Components were mostly identifiable even with the add-ons new to the participants. One of the primary reasons that participants failed to identify a component was because of the change in the shape post adaptation. For example, the diode with the ring-shaped add-on (70%) feels like a cone whereas participants remembered that the original diode was shaped like a cylinder. Another reason that the recognition accuracy was impacted was when big add-ons overshadowed the physical shape clues of small components, like the resistor (60%). However, after we showed our participants the correct answers after the study, they were all able to correctly identify the components.

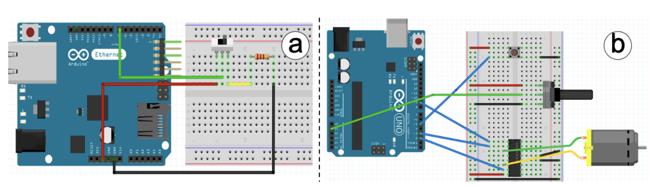

Figure 12: Tested circuits. (a) The simple circuit. (b) The complex circuit.

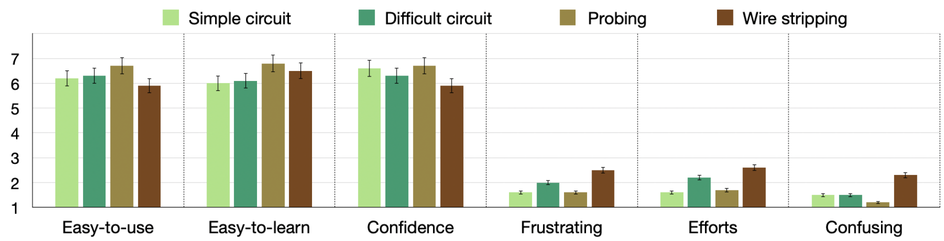

Figure 13: Subjective ratings with error bars showing 95% confidence intervals.

5.4.2 Constructing Circuits. The average success rate for the simple circuit was 86% (SD = 16%) (Figure 11). Among all the finished circuits, three were completely accurate. Within the errors, 10% occurred on the Arduino. The participants were able to complete the simple circuit with an average task completion time of 6.7 minutes. For the complex circuit, P7 decided to quit halfway into the task, so we removed their data from our analysis. All the rest were able to complete the task with an average task completion time of 17.3 minutes. The average success rate of the nine finished circuits was 83% (SD = 14%). Within the errors, 13.9% occurred on the Arduino.

The result is indeed encouraging considering that constructing a circuit was nearly impossible in Study 1 without the adaptations. As expected, the tactile labels on the breadboard allowed the participants to roughly locate a target hole, whereas the audio feedback of the location of an inserted component allowed them to confirm that the component was inserted into the right place. A participant said *"through the audio feedback I could tell whether I was doing right or not. I remember last time without the audio I had no idea where I inserted the component"* (P4). The participants also found the vibration feedback helpful. A participant told us that *"Vibration was as important as the voice output as I could tell if I inserted a component firmly or not"* (P2).

The participants also liked that the pins of the components were stiffer. A participant told us that *"it is nice that I didn't need to be worried about accidentally bending the resistor pin, which could be a disaster to fix"* (P9). The pin of the inserted components was also easier to find through the proxies or wire slots, making it easier for the participants to connect the wires. A participant said *"the wire slots were definitely helpful. All I needed to do was to follow the slot and be assured that the wire was in the right hole. I remember the last time I could not tell where I ended up inserting the wires"* (P2). Another participant said *"I found the wire slots super helpful as I could tell whether I was placing the wire above the right hole. Last time, I had to be very careful because if I pushed outside a hole, I bent the header"* (P1).

From the results, the complexity of a circuit had an impact on how well our system could help circuit construction. For example, with the breadboard becoming more crowded, wiring was more challenging as the add-ons could be occluded by the nearby wires or components. For example, the IC's pin_3 could be hard to find if a jumper was inside the slot of pin_2 (Figure ??a), along with the slide switch's pin_3 if the first two slots were taken (Figure ??b). Another common cause of a location error was related to the lack of audio feedback on the row coordinates. For example, the button and IC must be placed on row E or F, but they were often misplaced in a wrong row since the participants received no feedback. Finally, another important finding was related to a design issue in the description of the location information. The current design described all the locations using the coordinate of the breadboard even for the pins of an inserted component. For example, when a user inserted a wire next to the IC's pin_2, the audio feedback described the location as "column 21" rather than "pin_2". With this counter intuitive information, many of our participants ignored the audio feedback later in the task when wiring because they found it hard to use a breadboard coordinate to inform whether they had connected a wire to a component pin of interest.

5.4.3 Probing. Our participants were able to achieve an average success rate of 90% (SD = 21%). Eight of ten participants were able to achieve a success rate of 100%. Overall, it took an average of 17.74 s (SD = 9.75) for the participants to probe a component. Similar to the wiring task, the participant primarily used the wire slots to count and probe the component pins. A participant said *"the slots were useful as they made the pins so easy to identify. I remember last time it was so hard to stay with the pins"* (P2). However, probing was more challenging on the component pins that were only identifiable through the divider of two adjacent slots (e.g., odd pins of the IC) because there was no physical guidance to hold the probe tip in place.

5.4.4 Stripping Wires. The average success rate of wire stripping was 83% (SD = 28%), which was significantly higher than in Study 1 (e.g., 43%; $t_{18} = 2.97$, $p < 0.05$). The success rate for the 0.2 mm, 0.4 mm, and 0.6 mm wires were 80%, 70%, 100% respectively. Seven out of ten participants were able to successfully strip all the three wires with an average task completion time of 25.33s (SD = 13.2) to stripe a wire. Participants found the slot selector helpful for

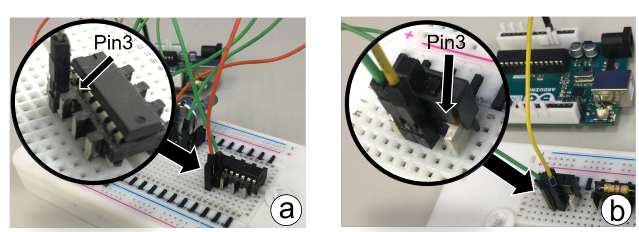

Figure 14: Hard to find pin_3 when (a) there is a wire header inside pin_2 slot or (b) the neighbouring slots were taken.

locating the desired blade slot. The wire guide was also effective in preventing the wire from slipping off the blade. P4 said *"I was much more confident and less frustrated this time as I did not have to be worried about where the wires went".*

However, a major drawback of the passive system is the lack of feedback regarding whether the plastic insulation is completely cut through. This is particularly true for the thinner wires (e.g., 0.2 and 0.4 mm). While most of our participants were able to pull the insulation off the wire even if it was not completely cut apart, P1 and P3 did not complete the task for the 0.2mm and 0.4mm wires because they were unable to apply enough force since they were not strong enough.

5.4.5 Subjective Feedback. Figure 13 illustrates mean subjective ratings for all the tasks. Overall, the participants found our tools easy to learn (6.35, SD = 2.84) and use (6.28, SD = 3.31). The participants liked the universal design of our add-ons. A participant said, *"the way how the wire slot works are the same across all the add-ons so after I learned the first one, I was able to use any new components"* (P8). With our tools, the participants were also able to complete the tasks without significant frustration (1.95, SD = 3.47), effort (2.03, SD = 4.58), or confusion (1.63, SD = 2.95). A participant told us *"I knew when I made a mistake, and I could fix it by myself. It was great that I did not have to ask anyone for help"* (P8). Most of our participants had never considered electronics-related fields as potential education or career opportunities, but many of them expressed their interest in further exploring electronics after using our tools and learning about its potential in STEM education. A participant told us *"I thought I couldn't do electronics or anything that is related but now I want to learn more about what I can do"* (P10). Another participant said that *"I always wanted to be an air conditioning mechanic, and I see it happening in the future if I can learn some basic electronics with these tools. I can even imagine that with these tools, I may be able to get a professional certificate in engineering... I hope that by showing people what blind people are capable of achieving with the help of these tools, more job opportunities can be provided to us"* (P7).

6 LIMITATIONS AND FUTURE WORK

Through this project, we have learned several lessons that may be beneficial to the community. In this section, we share insights we have gleaned from our experiences, discuss the limitations of the current work, and propose future research.

Add-on adaptations. One of the design goals of the add-ons was to make the component pins more accessible using larger proxies. The main trade-off is the increase of component size. As a consequence, breadboard circuits could be more crowded, thus harder to construct, understand, or debug. Our plan for future research is to optimize the size of the add-ons and breadboard.

Generalizability. Our adaptation designs are primarily based on pin layout, making them easily generalizable to similar components. For example, a 2-pin design can be used for components that have two pins (resistor, photocell, LED) with little or no modification. In the future work, we plan to implement a design tool (e.g., [12]) to support the design and fabrication given the inputs such as values (e.g. resistance), polarity, form-factors of components, etc.

Study. We invited the same group of participants for both studies, which may raise concerns regarding possible learning effects. However, we planned our studies at least 5 days apart to minimize the learning effects. Additionally, components and tools used in Study 2 had adaptations which made their tactile properties significantly different, so we believe the learning effect is negligible. Regardless, we will test AccessibleCircuits with more people in the future. While the current results demonstrate the existence of accessibility issues in the circuit prototyping environment, future research needs to investigate deeper into the accessibility barriers in the components and tools that are not included in the current work (e.g., self-adjusting wire stripper). Our current research focuses on circuit prototyping, but accessible learning materials are equally important. Future research will also focus on understanding how well the proposed circuit prototyping environment could work with the existing circuit learning environment [13]. We also plan to conduct small sessions of learning studios, composed of lectures and lab exercises. Additionally, we will seek to understand how well our system will work to support BLV students' learning activities in real-world scenarios.

Feedback. Feedback is essential to circuit prototyping but not all the information has to be presented using audio. Creative designs in passive haptics utilizing novel tactile labels or landmarks could allow the system to be developed at a low cost and deployable at scale to the broad BLV community. For example, our current study shows the need to provide feedback for row coordinates. Instead of using audio, some rows can be highlighted using a groove. This way, the user can tell whether an IC is inserted in row E or F by feeling the groove. In addition, users should be able to identify when a circuit is already presented with multiple connected components in the same column. A possible solution is to allow the user to first listen to the pin columns of all the connected components when a pin is touched. The user can then verify the column by touching the tactile label with audio feedback on column location of component pins provided. This can be easily added to our current system and will be included in future work.

Debugging. Circuit errors are inevitable [10, 15], and common errors such as miswiring, power management, and incorrect components often require significant time and effort to debug [10, 15, 37, 38]]. These challenges are common for sighted people, but they are magnified for learners with BLV, especially those without technical experience to prevent or diagnose hardware errors. Tools have been developed to help users debug hardware errors [1, 15, 37, 57], but additional research needs to investigate accessible circuit debugging environments.

Collaborative work. Working on circuit projects in a group of two or more is a common practice in a classroom setting, makerspace, and beyond. With the tools developed in this research, issues may arise in shared settings, where people with BLV may not be able to follow along when their BLV or sighted partners are constructing a circuit, as students may have a different mental image of the circuit task progress. Our future work will focus on understanding the barriers in collaboration between students of different visual abilities and to create and evaluate new tools to facilitate such collaborations.

7 CONCLUSION

In this paper, we describe the design and development of low-cost, 3D printable add-on components to adapt existing electronic components and tools for users with BLV in the maker community. Our design was informed by an initial user study with users with BLV where we observed several barriers to entry for standard electronic components and tools. Through an iterative design process, we created components to adapt breadboards, microcontrollers, electronic components, and wire strippers to make them more accommodating for users with BLV. We accomplished this by creating components that provide additional information or landmarks about specific holes and pins on electronic components, modify existing tools to make them easier to use for users with BLV, and provide additional non-visual feedback (e.g., audio and tactile) when completing certain tasks in creating a circuit. Our design also aimed to use low-cost materials and accessible technology through smartphones and 3D printers, so that more users in the BLV community would have access to the add-on components. In a follow up user study, we tested the effectiveness of our add-on components and found that users were much more accurate and quicker in tasks with our components. Through this follow up study, we also received overwhelmingly positive feedback from participants, and many of them hoped that this work would lead to a more accessible career in electronics and STEM for people with BLV in the future.

ACKNOWLEDGMENTS

This research was supported in part by the Ministry of Science and Technology of Taiwan (MOST109-2634-F-002-032, 109-2218-E-002-026, 109-2218-E-011-011), and National Taiwan University. We thank our anonymous reviewers for their suggestions. We also thank the participants of our study.

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A TABLES OF THE BLIND ENGINEER'S TASK COMPLETION TIME USED FOR DETERMINING THE TIME THRESHOLD FOR STUDY 1.

Table 1: Task1. Identifying Components.

Item	Second	Item	Second
Resistor	2	Diode	2
Photocell	2	Slide Switch	1
Temperature sensor	3	Transistor	2
Button	1	Potentiometer	2
Servo	2	DC motor	2
Piezo buzzer	2	IC 16pin	2

Table 2: Task2. Inserting and Connecting Components.

Item	Second	Item	Second
Diode	72	Temperature sensor	75
Button	128	IC 16pin	111
Wire (0.2mm)	184	Wire (0.4mm)	90
Wire (0.6mm)	50		

Table 3: Task3. Understanding Existing Circuits – I.

Item	Second	Item	Second
Structural information	210	IC 16pin	98
Temperature sensor	70	Slide Switch	70
Wire (0.2mm)	22	Wire (0.4mm)	31
Wire (0.6mm)	25		

Table 4: Task3. Understanding Existing Circuits – II.

Item	Second	Item	Second
Structural information	132	Potentiometer	130
Diode	30	Button	23
Wire (0.2mm)	35	Wire (0.4mm)	19
Wire (0.6mm)	25		

Table 5: Task4. Stripping wires.

Item	Second
Wire (0.2mm)	65
Wire (0.4mm)	28
Wire (0.6mm)	10

Table 6: Task5. Probing.

Item	Second
Diode	65
Temperature sensor	18
Button	17
IC 16pin	30
Potentiometer	50