TronicBoards: An Accessible Electronics Toolkit for People with Intellectual Disabilities

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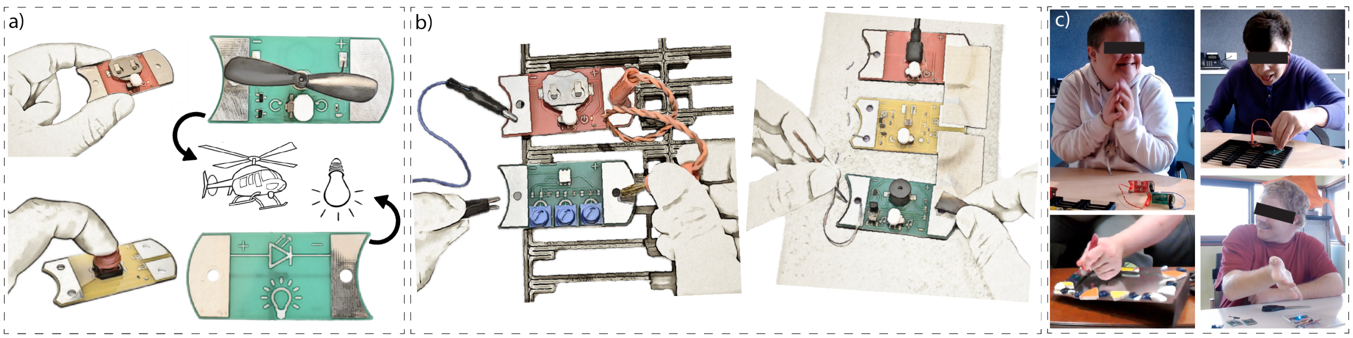

Figure 1: TronicBoards is an electronic toolkit that includes a) easily graspable, manipulable and understandable modules, b) multiple connectors that accommodate varying motor skills, stands to assist stabilization, visual and tactile cues like traffic light colors and unique edge shapes to assist connection order. It provides participants with a range of intellectual disabilities the opportunity to (c) enjoy the experience of circuit making through a personal sense of agency.

ABSTRACT

Engagement with electronic toolkits enhances people's creative abilities, self-esteem, problem-solving skills and enables the creation of personally meaningful artifacts. A variety of simplified electronics toolkits are increasingly available to help different user groups engage with technology. However, they are often inaccessible for people with intellectual disabilities (IDs), who experience a range of cognitive and physical impairments. We designed and developed TronicBoards, a curated set of accessible electronic modules, to address this gap. We evaluated it one-on-one with 10 participants using a guided exploration approach. Our analysis revealed that participants were able to create simple sensor-based interactive circuits with varying levels of assistance. We report the strengths and weaknesses of TronicBoards, considering participants' successes and challenges in manipulating and comprehending toolkit components, circuit building activities, and troubleshooting processes. We discuss implications for designing inclusive electronics toolkits for people with IDs, particularly in considering design elements that improve functionality, comprehensibility and agency.

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CCS CONCEPTS

• **Human-centered computing** → **Accessibility design and evaluation methods**; *User interface toolkits*; • **Social and professional topics** → *People with disabilities*.

KEYWORDS

Accessibility, Electronics Toolkit, Intellectual Disabilities, Computational toolkit

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1 INTRODUCTION

Electronic and computational toolkits can facilitate the creation of circuits and digital artifacts that support the development of STEM knowledge, creativity and logical thinking. A number of these toolkits have been developed in recent years to engage diverse user groups in playful, hands-on circuit building activities (e.g., [5, 5, 11, 12, 16, 28]). In addition to skill building, interaction with electronic toolkits has been shown to improve self-confidence and mental health by facilitating a sense of agency and enjoyment [47, 51]. Unfortunately, people with intellectual disabilities, who have a range of cognitive and motor skill requirements, have limited options in this space, in part, due to the accessibility issues of existing toolkits. Hence, they often miss the opportunity to experience the benefits arising from being involved in the digital artifact-making process.

In order to make electronic toolkits accessible to people with intellectual disabilities, researchers have typically adapted off-the-shelf toolkits to make the individual modules more discernable and support better handling and manipulation [18, 22]. Although these altered toolkits have had some measure of success, the authors noted several accessibility issues related to underlying module design (e.g, unmodifiable tiny controls for switches and potentiometers) [22]. There has been very little prior work [17] that has considered designing custom inclusive toolkits to accommodate the diverse and special needs of this population. TronicBoards aims to address many of these issues with a custom electronics toolkit that can expand the circuit-making activities of individuals with a range of intellectual disabilities.

We designed and developed TronicBoards based on prior work from literature and our reflections from preliminary workshops with individuals with IDs. TronicBoards consists of a range of accessible custom-made printed circuit boards covering power, action, and sensor module categories and multiple connector alternatives to cater for diverse abilities and interests. It has also been designed to assist easy physical manipulations and provides several visual and tactile affordances to assist comprehension of toolkit components and circuit structure. We evaluated this toolkit with 10 participants with a range of intellectual disabilities (assisted as required by disability support workers) during one-on-one sessions using a guided exploration approach. By conducting a thematic and interaction analysis of these sessions, we found that TronicBoards lowered the cognitive and physical barriers to electronics circuit making. We also reveal several benefits of TronicBoards related to facilitating a sense of agency and enjoyment. However, we also identified several pitfalls in our design. We discuss areas that require improvements, including refinement to enable more independent and customized physical manipulation, comprehension and troubleshooting, and error-less circuit making.

Our contributions include: (i) design and development of TronicBoards; a custom-made accessible electronics toolkit for people with intellectual disabilities; (ii) empirical evidence from one-on-one evaluation sessions of how people with intellectual disabilities engage with TronicBoards toolkit in terms of what they could achieve and the challenges therein; and (iii) insights regarding the affordances necessary to support a personal sense of agency. These contributions take one step forward to making electronics-based circuits more accessible for people with intellectual disabilities, a timely and important area that has the potential of improving their self-esteem, empowerment and skillset.

Our overarching vision with TronicBoards is to provide an opportunity for marginalized communities, especially people with disabilities, to move from passive recipients of technology to active designers of personally meaningful computational technologies. People with disabilities have specialized needs much like other marginalized communities [26, 27]. We envision a future where the tools and systems are flexible enough, so they can craft smart artifacts and potentially their own assistive devices independently or with limited support from caregivers and disability support workers. More broadly, our goals are to help them become active participants in a mixed-ability maker culture [2], which contributes to learning opportunities as well as social well-being. Towards this end, the work presented in this paper provides empirical evidence to better understand how to design accessible electronic toolkits to improve the sense of agency in people with intellectual disabilities.

2 BACKGROUND

Within the scope of our work, we identify *intellectual disabilities* (IDs) as a group of neurodevelopmental disorders characterized by limitations in general mental abilities, such as reasoning, problem-solving, planning, abstract thinking, judgment, and learning [3, 42]. These limitations commonly cause impairments in cognitive functioning (e.g., memory, attention, perception) and social functioning (e.g., communication, language) [3, 42]. Typically, severe IDs are also accompanied by impairments in motor functioning (both fine and gross movements and motor planning) and sensory functioning (vision and hearing deficits and also hypersensitivity to lights, sound and touch) [42]. We acknowledge that there are varying definitions and preferred terms to describe intellectual disabilities depending on country, culture, and context. We utilized the term "intellectual disability" because it was the term used by the participants and disability support organizations. This terminology has also been widely adopted in the HCI research [17, 25, 49].

Individuals with IDs are one of the most marginalized and underserved groups in society, with many lacking access to developmentally appropriate education and training [50], particularly in accessing digital technologies [39] and STEM-related tools that are now commonly available to the general population. Engagement in technology or STEM-related activities not only facilitates creativity and learning of new cognitive skills but also impacts social communication and collaboration [15]. Tangible digital technologies and toolkits further support improving motor and sensory skills through practice for individuals with IDs. But perhaps more importantly, these technologies help provide a sense of control and raise a personal sense of agency and autonomy in performing daily activities [15, 39]. Moreover, we strongly believe that despite impairments, people with IDs also have a right to access and utilize emerging technology (e.g., electronic and computational toolkits) in much the same way as the rest of society, albeit in a more inclusive and appropriately designed way.

3 RELATED WORK

In recent years, there have been a plethora of computational, maker and electronic toolkits for craft, creativity, and STEM-related activities. Some of these toolkits have also catered to the needs of specific user groups such as older adults, children, and, more recently, individuals with disabilities. In this section, we identify some of the design considerations and affordances employed by prior work in this area that have informed the design of TronicBoards for people with IDs. We cover a curated list of related work from an accessibility perspective. Refer to more recent surveys on electronic, tangible and computational toolkits [7, 52] for a more comprehensive overview.

3.1 Accessibility Features of Existing Toolkits

Simplified electronic toolkits are increasingly available for STEM education. Some of these toolkits, including the BBC Micro:bit [38], Snap Circuits [16] and Little Bits [5], abstract electronics and programming or provide accessibility features to facilitate the construction of circuits and programs. Little Bits and Snap Circuits, for example, have larger modules that encompass the tiny electronic components to improve graspability. They also include indicators such as arrows, plus and minus signs to facilitate the understanding of connections [5, 16]. Actual electrical connections with these kits are accomplished via magnets and snaps as opposed to breadboarding or soldering to simplify the circuit building process. Other kits such as Micro:bit support jumper wires, crocodile clips, and banana plugs to better leverage the existing Maker and DIY electronics ecosystem. To improve the craftability of electronics in textiles, the LilyPad Arduino [11] uses relatively large conductive pads with holes to facilitate connections through conductive thread. Alternatively, Squishy circuits employ conductive dough that can be made with readily-available ingredients to provide "chunky" connector options [21, 30]. Since dough can be shaped to form connections, Squishy circuits helped participants learn that a closed circuit is required to conduct electricity and actuate components [45].

In designing an electronic toolkit for individuals with IDs, we were influenced by these prior toolkits and utilized many of the same techniques for graspability (particularly for individuals who may have secondary motor issues), comprehensibility and simplified connections. Furthermore, remaining flexible in the design to accommodate a variety of circuit construction methods as in the Micro:bit was recognized as most suitable to facilitate circuit building for diverse users who would fall somewhere in the ID continuum.

3.2 Altering Toolkits for Inclusivity

Previous research has also examined taking existing electronic toolkits and adapting them for different user groups such as older adults and children. The Craftec toolkit system, for example, makes the LilyPad Arduino's connection points more accessible to aid older adults' crafting practices [28]. Its soft and hard versions reduced short circuits and facilitated better integration of electronics into craft artifacts in workshop evaluations with older adults [28, 29]. Specialized kits based on Lilypad, such as EduWear [32], also exist for children. EduWear breaks out the sensors and actuators into easy to sew textile patches for younger children. Since younger children are still developing their motor skills, research has also examined single-function electronic modules that can be combined in a magnetic socket mesh to create complex interactive clothing [33]. These toolkits highlight the importance of facilitating electronic connections in a non-frustrating manner. Chu et al. found that alligator clips, clothing snaps, and D-sub pins were the most usable and aligned with young children's abilities [13]. These findings informed out choice of connectors (particularly the use of alligator clips) for our toolkit with our target user group.

Apart from children and older adults, a number of adapted toolkits also exist for individuals with IDs. LittleBits Go LARGE incorporates the LittleBits modules into 3D-printed bases to increase the surface area for easier handling and manipulation [23] for people with learning disabilities. They also augmented the design of the modules to make their functions more obvious and understandable, particularly the shape-based differentiation between input and output terminals [22]. Similarly, Gotfrid and Shinohara, introduced circuit design to participants with IDs by embedding LilyPad components into puzzle pieces and decreasing the level of fine motor control required to sew circuits [18]. They included colored lines to indicate which threads in different puzzle pieces could connect together. In a pilot study, they found that users were able to create their very own e-textiles. However, these kits also identified areas of improvement, particularly for people with motor impairments. Most notably, Hollinworth et al. found that participants had challenges manipulating tiny controls such as sliding switches and variable potentiometers (e.g., adjusting the color of an RGB LED) to customize the modules in the LittleBits Go Large project [22]. This highlights the need for a solution that addresses these issues, such as individual electronic component selection (e.g., larger or custom switches, easy-to-turn potentiometers) in a more holistic manner.

Even though prior work in this area has explored different affordances (e.g, colored lines, differentiated input and ouput) to cognitively help users connect components in the right order, related studies also report instances of participants creating malfunctioning circuits by arranging modules in non-standard ways [22, 23]. Designing affordances of module functionality (i.e., what they are intended to do) and controls (i.e., how to use them) to be perceivable is still an active research area, especially for people with IDs who have cognitive impairments.

A key aspect of our work is in trying to support a diverse set of cognitive and physical assistance requirements. In Gotfrid et al.'s modified Lilypad toolkit, they provided conductive paint and crocodile clips to electrically connect conductive thread as alternatives to sewing [18]. They found that while one participant could stitch components into a fabric with some challenges, the other participant relied on researchers' hands for sewing and applying pressure on other alternative connectors. These findings imply the importance of minimizing the physical efforts required in stabilizing and applying pressure for those who face challenges to make engagements with the toolkits more accessible. Ellis et al. also report different levels of assistance required during the remote workshops that involved circuit making using conductive tape, highlighting that the assistance needs to be provided without taking the control away from the participants [17]. Hence, supporting multiple ways of accomplishing the same electronic goals through a variety of connectors and components was considered important.

3.3 Custom Toolkits for People with Intellectual Disabilities

There have been several custom computational toolkits that have focused on specific activities, including audio-enhanced weaving [8], learning basic computing concepts through musical physical blocks for visually impaired participants [4], and controlling audio playback as a form of therapy for people with cognitive disability [20]. However, there are few custom-made toolkits designed and implemented exclusively for those with IDs and electronic-based making.

Magic Cubes, developed by Lechelt et al., consists of square printed circuit boards (PCB) that can be assembled to form a cube. Once assembled, these cubes can be utilized to explore sensor-actuator effects through guided discovery [36]. The toolkit was evaluated in a special-needs classroom with students primarily diagnosed with autism spectrum disorder (ASD). Although the focus was to study collaborative learning in a mixed setting rather than toolkit design, the authors did warn against using off-the-shelf equipment without considering affordances that enable embodied debugging and collaboration (especially in group settings) [36].

Perhaps the work closest to our work is TapeBlocks [17], which was custom designed as a maker toolkit for people with IDs. It consists of conventional electronics embedded in large foam blocks with conductive tape connections. The connection areas are large, and blocks just need to be held together to form complete circuits. The use of bi-directional electronic components, such as bicolor LEDs, avoided imposing directionality of connections and minimized failures [17]. TapeBlocks focused on lowering the threshold for engagement and was successful in helping participants build simple, meaningful electronic artifacts. However, during the evaluation, the authors found that makers, coaches, and people living with IDs were interested in how to progress from TapeBlocks to more advanced making activities.

Our work focuses on this next step in the research pathway through a custom PCB toolkit that expands the range of circuit-building activities that people with intellectual disabilities can take part in. Much like the designs showcased in this section, building custom hardware modules can better integrate the design choices from the literature as well as new ideas generated through practice in a cohesive package. Moreover, developing custom PCBs can be achieved at low cost and effort due to the open-source electronics and the Maker movement.

4 PRELIMINARY WORKSHOPS

Our work is also informed by our relationship and practice with local community disability support organizations. We have been regularly working with these organizations to better support technology initiatives for several hundred people living with IDs. Over the past five years, we have conducted multiple maker workshops to introduce physical computation and tangible electronics to people with intellectual disabilities using a range of electronic toolkits, materials, and equipment. Table 1 summarises these preliminary workshops in chronological order.

4.1 Participants and Facilitators

Participants of these workshops were adults aged over 18 years, who had an intellectual disability and required low to high support for daily living. High support participants often had motor issues. Each workshop represented a balanced spread of gender. Overall, 148 adults with IDs participated in 6 workshops listed in Table 1.

Coaches of the workshops were researchers (including volunteers from our university) and support workers from various disability support organizations. They provided both physical and cognitive support for participants to complete the activities. The number of participants assigned per coach varied from 1 to 8 depending on the level of support that they required.

4.2 Workshop Sites and Duration

Workshops were typically conducted onsite, either at the facilities of the disability support organizations or at the university's multiple campuses. The workshops that had a majority of moderate to high support participants as opposed to low support participants were typically longer in duration. Overall, the workshops were 45 - 90 minutes in length, and we aimed to keep them shorter as it was difficult to maintain participants' engagement and concentration levels for longer durations.

4.3 Workshop Activities

Types of activities that we used within workshops varied, and some workshops (e.g., 3rd to 5th workshops listed in Table 1) facilitated multiple activities to meet participants' interests. Activities included making threaded or wired circuits in felt (Figure 2a,d), modeled circuits within polymorph (thermoplastic) or clay (Figure 2b,d) and taped circuits on foam blocks (Figure 2c,e). Participants were also provided with craft items to decorate their circuits during all the activities.

Some activities were modified versions of activities from previous workshops that aimed to better adapt to participants' skills. For example, during the first workshop listed in Table 1, we noticed that only a very few low-support participants could complete traditional needle and conductive thread-based e-textile circuits. We identified (a) limited support with component comprehension and arrangement with respect to the individual modules (b) small-sized modules and connecting holes ($\sim$ 2 mm diameter), and (c) skills required in determining thread lengths as major issues with this activity. In later workshops, we modified this activity to eliminate needles, include stiffer connectors, and reduce planning efforts. In this version, participants threaded in and out long wires of an LED (using their hands) through laser-cut holes in a piece of felt (see Figure 2a), and the circuit was completed by sticking conductive tape to the ends of the wires to connect a 3V coin battery, where this connection was stabilized with a peg. This additional in-built support improved the engagement but compromised the flexibility of the circuit structure as well as limited the opportunity to practice planning and fine-motor skills.

4.4 Design Choices Based on Reflections

During the workshops, our participants created several circuits with support staff, added decorations on top of built circuits (see Figure 2d,e) and enjoyed their makings. However, our reflections [14, 46] on these workshops point to several reoccurring accessibility issues in the toolkits that we used, sometimes with relation to the issues reported in related works. These issues informed many of the design choices implemented in the TronicBoards toolkit.

During the initial workshops, many participants experienced motor issues in manipulating small sensors and actuators (e.g., 5mm LEDs). Consequently, in subsequent workshops, we integrated small electronics components into foam blocks. The dimensions of the foam blocks were approximately 7 cm x 3.5 cm x 3.5 cm. Although they were easy to manipulate, they could not be easily integrated into participants' crafts or personal items, especially due to their height and volume. This indicated a need for *modules that are large and compact enough for integration*. Therefore, we decided to use standard PCBs with a slightly small area than foam blocks (6.5 cm x 3 cm) with integrated electronic components (that add up to $\sim$ 1.5 cm height) for the TronicBoards toolkit.

Participants also experienced difficulties in manipulating and recognizing tiny controls and connection points (e.g., slide switch in

Table 1: Summary of Previous Workshops

# of Participants	Support Level[1]	# Coaches: Participants	Duration (minutes)	Activities and Materials
24	Low	1:5	45	Making circuits on felt using Lilipad components, conductive thread and laser cut holes
25	Low	1:6	45	Molding creations using oven bake clay and lighting them up using standard LEDs
16	Moderate	1:4	90	Making circuits on laser-cut felt using long-wire LEDs and conductive tape, Molding creations using polymorph and lighting them with long-wire LEDs, Pushing together pre-made actuator, sensor and power blocks to make connections, Making circuits on foam blocks using off-the-shelf electronic items and conductive tape, Decorating the textile and block circuits using off-the-shelf crafting materials
35	Low	1:5	45	
40	Low	1:8	45	
8	High	1:1	60	Pushing together pre-made actuator, sensor and power blocks to make connections

[1] As described by support workers and aligned with the definitions provided in [43]

Figure 2: Circuit making activities with (a) wires threaded through felt, (b) polymorph molds and (c) taped blocks at preliminary workshops and their outcomes: (d) decorated textile circuits, butterfly molds and (e) train characters with LEDs.

the Lilypad battery holder and their ~ 2 mm diameter holes). Hence, custom-made knobs for switches, off-the-shelf *controls with larger knobs*, and large connection pads and holes were design aspects we integrated into the TronicBoards toolkit.

Our participants also displayed confusion about component order (e.g., connecting a switch in parallel to an LED but not in series). This issue pointed to the need for additional cues such as *color-coding*. Based on a suggestion from a disability support worker, we decided to use the traffic light metaphor in the TronicBoards toolkit. We also decided to use uniquely shaped board corners as an alternative tactile cue to color-coding.

During the workshops, participants demonstrated issues in recognizing the various electronics items and modules, limiting agency in terms of what they could try. We often had to demonstrate components in action (which could have disturbed participants' "aha" moments) or use pictures on instructions sheets. To overcome this issue, we printed icons and symbols related to functionality on the individual boards in our new toolkit.

Many participants also could not recognize the polarity of electronic components (e.g., they connected negative terminals of LEDs to the positive terminal of batteries). One issue was that the +/- marks used in some of the components (e.g., Lilypad LEDs) were not very visible. Participants may also not have understood the meaning of these signs. Hence, we decided to include *multiple clear indicators to ease the comprehension of the polarity* of TronicBoards modules by using larger +/- signs closer to the module edges and shaping the module edges to have concave and convex shapes, thereby reflecting the direction of positive current. To reduce the failures that might arise from this cognitive challenge, we also replaced standard LEDs with bi-color LEDs in subsequent workshops. Similarly, we decided to use bi-directional components where possible in the TronicBoards toolkit as an *in-built support to reduce failures*.

Our participants also demonstrated varied abilities in the use of physical connectors. Some of the issues included applying pressure on the pegs used for holding batteries and wires, taping circuit components to foam blocks, and passing needles through tiny holes in the Lilypad components. However, these activities were also seen as opportunities for practicing fine motor coordination skills. Furthermore, we discovered that a single connector type did not universally *facilitate the integration of circuits into different form factors*. Hence, we decided to support *variety and flexibility in connections* in the TronicBoards toolkit to better accommodate the range of needs of participants with IDs. Given that our workshops lacked easy-to-plug wire connector types, we planned to include crocodile clips and banana plugs, in addition to conductive thread and tape used in the workshops.

The preliminary workshops also informed the electronic component selection for the TronicBoards toolkit. In one of our workshops, we replaced LEDs with vibrotactile motors to accommodate the needs of a vision-impaired participant and expanded the color range of the LEDs to suit participants' interests. However, we could not accommodate all requests due to the limitation of the kits we used. For example, some participants requested music or melodies, which was harder to find as pre-built modules. Based on these experiences, we decided to support *variety and flexibility in modules* in the TronicBoards toolkit, including a module that plays different melodies and LEDs with customizable color.

In our workshops, participants wanted to control sensor behavior to achieve particular outcomes using conditional logic. For example, one participant who wanted to activate an LED in low light conditions had difficulty in doing so with just a LED, battery and light-dependent resistor. Consequently, we decided to embed conditional if-else logic as part of the sensor modules in the TronicBoards toolkit. To help facilitators modify sensor thresholds without virtual programming, we decided to include on-board tangible controls (e.g., potentiometers).

Based on prior literature and the design elements we identified in our workshops, creating a new toolkit was the necessary next step rather than modifying an existing toolkit.

5 TRONICBOARDS TOOLKIT

The TronicBoards toolkit consists of a graspable set of 14 single-sided PCBs, which are 3cm x 6.5 cm x 1.5 cm in size (Figure 4). The modules are color-coded into three simple categories, namely, power (red), sensor (yellow) and action (green). We implemented the traffic light analogy for board design (as also used in [17]) to scaffold module order (Figure 3) in circuit design activities, a salient issue from our preliminary workshops (Section 4.4). Figure 3 showcases a sample circuit consisting of a 3V coin cell battery board (red), a light sensor (yellow), and an RGB LED board (green) connected with strips of conductive tape. Since the light sensor rests in between the power and action boards, it has four connection holes. Each board type is also uniquely shaped (particularly the left edges) to support tangible recognition of the modules. The fabrication files for the TronicBoards toolkit along with the bill of materials (BOM) are publicly available at [48] under the Creative Commons copyright license (CC BY-NC-SA).

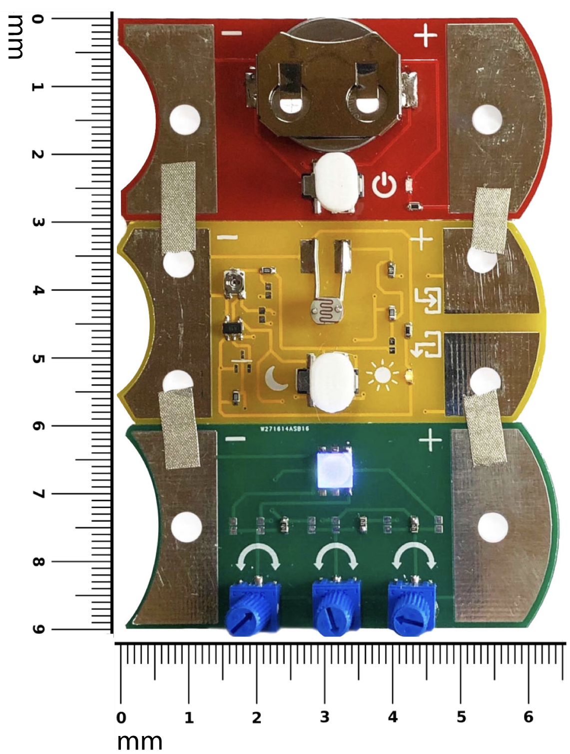

Figure 3: A sample circuit utilizing the battery, light sensor and light mixer boards connected with conductive tape. The traffic light metaphor is aimed at facilitating module order.

5.1 Module Design

We designed a curated list of modules with varying functionality and interactions (showcased in Figure 4) to accommodate the different needs and interests of people with IDs.

The battery (3V) and USB (5V) boards are two options for powering a circuit. Although the battery board is more flexible (can be used in portable settings), it requires more developed motor skills (for replacing batteries) when compared to the USB board. The USB board is current limited in case of potential mishandling or short circuits. Each power board also contains an on-off switch, so users can operate the circuit without disturbing the module contact points.

The action boards consist of two visual, two auditory and two tactile actuators that activate whenever power is applied. Half of these boards produced static outputs of (single-color, same-intensity) light, (monotonous) sound and (same-frequency) vibration. The other half provided on-board controls to customize the feedback. For example, the light mixer board has three knobs to mix red, green and blue colors, music board has a sliding switch to select between two pieces of melodies with two different tempos, and fan board utilizes a sliding switch to change the direction of rotation. The light board, vibration board and fan board include bi-directional actuators (i.e., they operate irrespective of polarity), thereby reducing failures. The bi-color LED in the light board warns the user by turning red color when connected in the wrong direction.

The six sensor boards include a: push-button, tilt switch, reed switch, touch sensor, light sensor and temperature sensor. Some of these boards embed if-else logic, supporting sliding switches to customize the sensor behavior. For example, the light sensor board can be configured to pass current to support different light conditions (bright or dark), using the on-board slider. Moreover, multiple sensor boards could be chained together to perform AND or OR logic.

5.2 Toolkit Affordances

The boards were designed with a number of affordances to support people with IDs, particularly in helping participants recognize tiny controls and module functions (as observed in many participants of our preliminary workshops). Apart from the distinct shapes and color coding, we chose large knobs for potentiometers and integrated custom 3D-printed switch covers to facilitate easy recognition and manipulation of controls. We also printed recognizable symbols in high contrast (e.g., sun, moon, doors, speaker, light bulb) on the front and back of the boards to suggest their functionality and purpose. To better support error recognition, each module contains a miniature LED or a main LED to indicate connection status. These large controls, together with recognizable symbols, and indication LEDs, borrow from prior work on physical widgets or Phidgets [19]. They expose functionality and state of the modules through visual and tangible displays.

The rear side of each board contains high-level circuit symbols associated with the board's main electronic component to support the development of technical skills for high-functioning participants in the long term. The placement of these high-level symbols is designed in such a way that when a set of boards are connected using conductive tape on a transparent clipboard, the circuit symbols and traces of tape produce the circuit diagram associated with the circuit.

5.3 Connectors, Tools and Stands

The boards in the toolkit can be connected using a variety of methods including, conductive tape, conductive thread, crocodile clips,

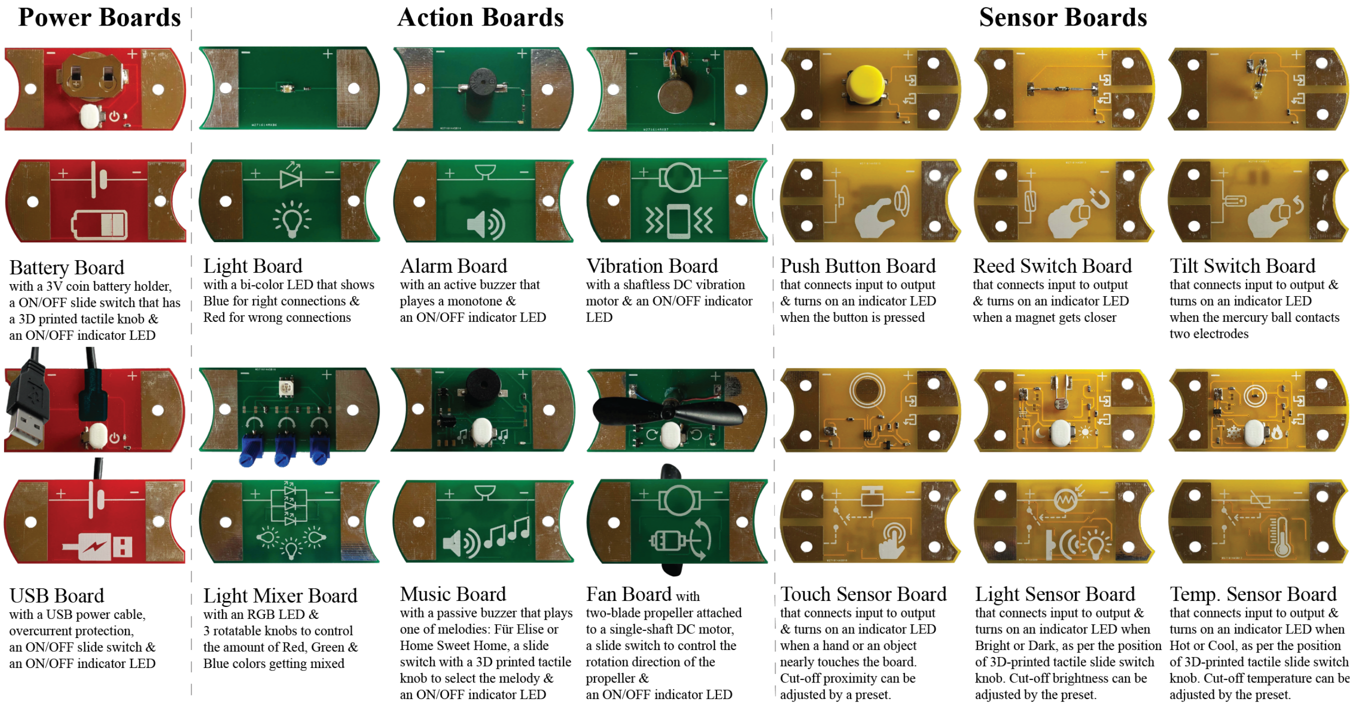

Figure 4: TronicBoards with brief descriptions of board functionality and controls

and banana plugs, as illustrated in Figure 5. Both prior work and our preliminary workshops have highlighted the need to support a range of motor skills and the ability to integrate circuits into a variety of materials. Conductive tape requires applying less pressure than banana plugs and crocodile clips but requires crafting skills in order to measure and cut the tape. Being able to cut with scissors is related to the concept of dignity in risk, and in light of that, even using such non-technical tools can improve the self-esteem and agency of people with IDs [40]. Although the wired connectors (e.g., banana plugs and crocodile clips) are the most reusable, they require bracing of the boards securely in order to make the connection. For this purpose, we utilized the 3D-printed stand designed to organize and carry the boards for transportation (Figure 6).

6 METHODS

To better assess the resulting toolkit, we conducted 10 one-on-one evaluation sessions over the span of 4 months. These sessions helped us evaluate participant engagement, comprehensibility and agency around the overall design of the toolkit for individuals with intellectual disabilities. All sessions were conducted with approval from the institutional review board of our university, and informed consent was collected before participation in the study.

6.1 Participants

We recruited 10 participants with an intellectual disability (4 males and 6 females, mean age = 40.42, SD= 19.18) from two local organizations that provide disability support services, including accommodation, education, training and recreational activities. The majority of participants required significant support for accomplishing daily tasks due to their communication, dexterity, attention and/or memory impairments. Table 2 details the demographic and disability-related information of the participants. Note while some participants experienced intellectual disability as the primary

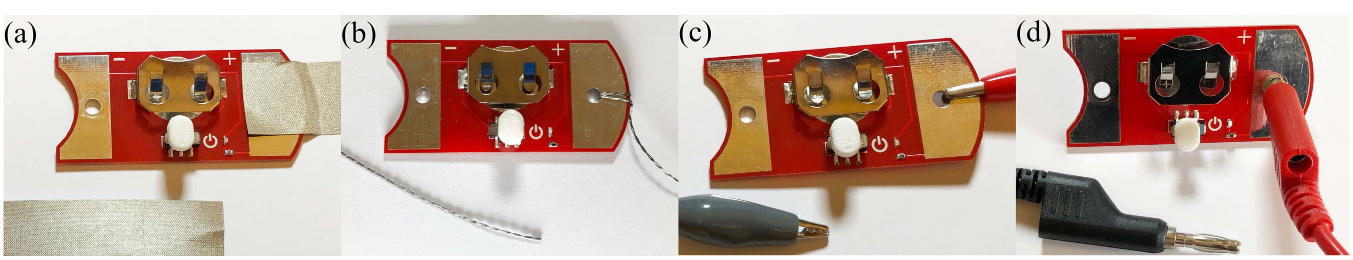

Figure 5: Connector Types: (1) conductive tape, (2) conductive thread, (3) crocodile clips, (4) banana plugs

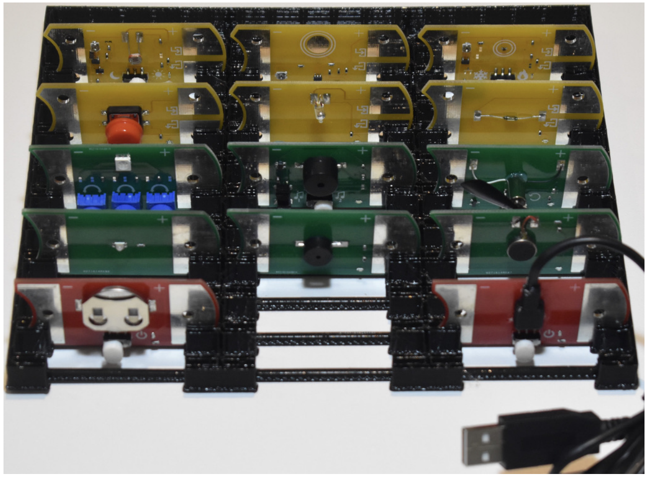

Figure 6: 3D-Printed Stand for TronicBoards

disability (e.g., P7, P8 and P10), others were diagnosed with another primary disability in addition to intellectual disability.

Table 2: Participant Demographics and Disability Details

ID	Gender	Age	Disability Details		
			Primary Disability	Secondary Disability	Supports Needed[1]
P1	Male	19	Autism Spectrum	Intellectual	Low
P2	Male	21	Autism Spectrum	Intellectual	Moderate
P3	Male	26	Autism Spectrum	Intellectual	Moderate
P4	Female	41	Intellectual	-	High
P5	Female	41	Down Syndrome	Intellectual	High
P6	Male	52	Mental health	Intellectual	Moderate
P7	Female	52	Down Syndrome	Intellectual	High
P8	Female	55	Intellectual	Motor (Hand)[2]	High
P9	Female	61	Down Syndrome	Motor (Hands)	High
P10	Female	69	Intellectual	Motor (Mobility)[3]	High

[1]As described by support workers and aligned with the definitions provided in [43]; [2] Dysfunctional left hand; [3] Wheel chair usage

6.2 Procedure of Evaluation Sessions

The first author of this paper conducted one-on-one evaluation sessions with the participants at 3 sites; one shared accommodation facility (P4, P7, P9) and two day service centers (other participants) of the disability support organizations that we worked with. Typically, a support worker was also available for part or the entire duration of the session, depending on the physical and intellectual needs of the participants.

We employed a form of guided exploration in our evaluation sessions. Guided exploration has been recognized as an inductive minimalist approach for teaching tool-related concepts and techniques [34]. It lets the participants use tools before providing them with information on related principles and procedures. Users are either presented with such information or helped to discover it for themselves when they demonstrate a need. Since this method facilitates immediate engagement with meaningful and realistic tasks while reducing the efforts required in training [34], we found that it was suitable for our participants, given that they had diminished attentional, concentration and memory capacity. Furthermore, since this method is flexible, the researcher could make on-the-fly slight modifications to the procedure to adapt to the diverse needs of our participants, as also commonly practised in maker spaces with people with disabilities [9]. Moreover, this process helps to make errors and error recovery less traumatic and more pedagogically productive [34]; therefore, we found that this method supports our goal of identifying improvements to TronicBoards while moderating participant frustration.

After providing some time to make the participants feel comfortable in the environment, the Tronicboards kit was displayed on the table. The boards were arranged on a 3D-printed stand (see Figure 6). The researcher encouraged the participant to pick up and explore the boards. As they were handling the boards, the researcher informally asked to guess what the boards could do. A participant could guess all or subset of the boards, depending on their interest and engagement.

Participants were then provided with wired connectors and guided to build their first circuit with an action board and a battery board. For example, a participant could choose a music board, attempt to use banana plugs, and move to crocodile clips, depending on their preference and motor skills. Similarly, the researcher provided guidance to build more circuits using other connectors, action boards and sensor boards of their interest for the rest of the study.

Throughout the study, the researcher provided different levels of assistance in response to participants' needs. The assistance levels spanned from verbal (direct and indirect), gestural prompts (pointing), model prompts (side-by-side and hand-over-hand demonstrations), and sometimes doing it for them [6, 41]. For example, as an indirect verbal cue, the researcher explained the traffic light analogy behind TronicBoard design to hint about board order. Support workers also assisted participants, specifically by facilitating communication by providing familiar language and guiding hand movements.

The researcher also contextually asked questions to understand participants' challenges of using and insights about TronicBoards. For example, the researcher asked questions to extract issues around manipulating connectors, difficulties in recognizing boards from their front looks (i.e., without referring to icons at the back), and insights about what they would like to make with TronicBoards (a wooden pen holder that had a Battery and LED board was shown as a probe).

We audio and video recorded all sessions. A Logitech webcam closely captured participants' expressions and an Insta 360 degree camera attached to a 2m tripod that captured participants' hand movements and their interaction with others. All the studies were conducted by one researcher to maintain consistency.

6.3 Analysis

The analysis was conducted by all the authors of this paper. We first analyzed the audio and video data deductively [10] with respect to the accessibility features we incorporated into TronicBoards. Specifically, we examined successes and failures with modules, connectors, circuit composition and troubleshooting. As we familiarized ourselves with the data, we derived codes inductively [10] and refined them to increase specificity in several iterations. Since the verbal content of many of our participants was notably limited due to their disability, we also analyzed their non-verbal interactions with TronicBoards and others in the study environment, incorporating an interaction analysis approach [31].

It is sometimes hard to understand what participants mean based on non-verbal cues such as gestures and emotions. In this space, it is vital to neutralize preconceived notions and avoid ungrounded speculations about what participants are thinking and intending [31]. For this purpose, we met as a group over several weeks to collaboratively view and discuss each video recording to arrive at agreements. We further analyzed the "periodicity" of certain events as suggested in interactive analysis; repeated occurrence of the same error is a well-grounded measure to extract instances of trouble experienced by participants with intellectual disabilities. Other concepts that we used from interaction analysis include: "trouble and repair" to analyze how troubleshooting occurred, "participant structures" to analyze how TronicBoards facilitated social interactions, and "rhythms" to analyze easy and difficult connector and circuit options. Overall, due to the above-detailed combination of deductive and inductive thematic analysis and interactive analysis, several rigorous findings; therefore, deep and complex insights emerged as reported in the next couple of sections.

7 FINDINGS

7.1 Engagement Levels and Overall Outcomes

The TronicBoards evaluation sessions typically lasted from 20 minutes to a little over an hour, depending on participant engagement and concentration levels. A majority of participants were actively and positively engaged in circuit-building sessions and carried out significant hands-on work, demonstrating their confidence and agency in using the kit. Participants celebrated many small wins, including recognizing modules, making successful connections, and being able to control modules through switches and knobs. They expressed positive reactions during these wins: big smiles, behaviors such as applauding, thumbs up and hands raising (see Figure 7), verbal exclamations ("it works, yes" (P5)), soliciting appreciation ("good job?" (P7)). Moreover, some participants were keen on explaining their circuits to support workers. Showcasing their creations was also critical for their idea of success (see Figure 8). However, we also observed some challenges and frustrations experienced by participants who required extra assistance from time to time (see Figure 10), as detailed in the subsequent sections.

Overall, each of our participants could make their own circuits, relying on varying levels of assistance. Exceeding our expectations, eight participants produced 5-6 circuits during this short-term study, and three of them tried all connectors types. The majority of circuits that they made were simple and consisted of a battery board and one of the action boards (e.g., music board, fan board) (as in Figure 7c). Each participant also made at least one circuit combining a sensor board with one or more action boards (as in Figure 8). However, our participants did not make more complex circuits involving more than one sensor board.

Two participants, who engaged with TronicBoards at their residence, collaboratively made personally meaningful electronic artifacts with our assistance. One participant decorated her personal mirror with a light board, battery board, conductive tape and glitter glue (see Figure 9b). Another participant utilized a music board with a battery board and enjoyed changing the melodies using the sliding switch (see Figure 9a). This circuit was assembled in a non-standard vertical configuration to make it hand-held and accommodate her motor skill issues.

7.2 Module Comprehensibility

Our participants' ability to comprehend the *functionality*, *controls* and *types* of TronicBoards greatly varied during the initial stages of the study (i.e., before making circuits). Successfully guessing the boards without assistance served as a game for some (P1, P4, P7) and provided a sense of achievement to others (Figure 7a). Those who faced challenges in this area showed improvements after trialing the boards or receiving cognitive assistance from researchers and staff. Participants often showed interest in learning by repeating

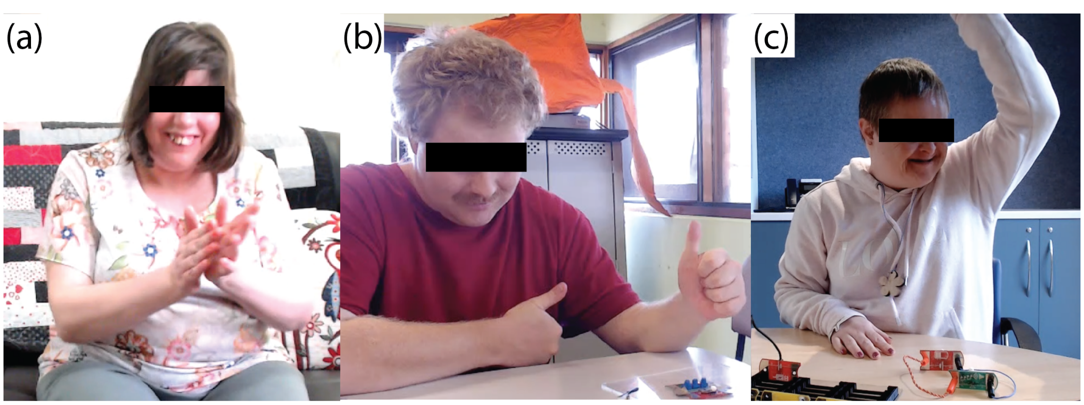

Figure 7: Participants' expressing positive gestural reactions including applauding, thumbs up, and hand raising after correctly guessing module functionality (a), producing their initial circuits (b,c)

Figure 8: Participants showcasing their circuits and abilities to staff members: (a) explaining how a tilt switch works (b) actuating a vibro-tactile motor, (c) showing how to control light with a reed sensor and magnet

suggested terms or guessing board names using direct or indirect cues.

We often provided assistance in directing participants' attention towards board cues, particularly the icons on the front and back of the boards. For example, the iconography on the music board (8/10 participants) and the light board (7/10) was very helpful for many participants. Other boards, such as the fan board (10/10) and push-button board (8/10), were aided by tangible and visual cues. To demonstrate their ability to comprehend, participants rotated the blades manually (P2, P4, P10) or suggested familiar names such as helicopter (P3, P8), "fan" (P9), "windmill" (P5, P10), "propeller" (P1), "aeroplane" (P7), and "blades" (P6). There were also instances where participants could only comprehend some boards to a limited extent; for example, multiple participants comprehended the light mixer as something to do with multiple lights. The tilt sensor was the hardest board, with none of the participants understanding its functionality. While the symbols, signs and icons were helpful to the majority of participants, a few required seeing the boards in action to comprehend their purpose.

However, many participants had difficulty in identifying the controls in boards and required assistance from a researcher or staff member. Once participants were able to operate or see the controls in action, they expressed their improved understanding of board functionality verbally in responding to the researcher's questions or through active engagement. For example, P3 said "it [light mixer board] changes color", P5 and P7 said "it [Fan Board] goes backward/ downhill," and P8 and P9 spent extended periods in experiencing haptic output of the vibration board and changing melodies of the music board, respectively.

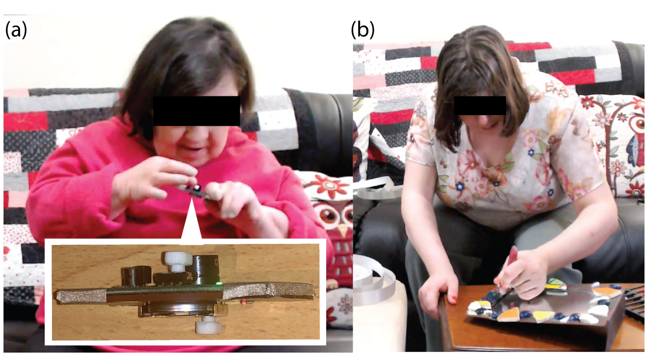

Figure 9: Participants' artefacts: (a) a hand-held music circuit with changeable melodies and (b) a personal mirror decorated with light board and glitter glue

The traffic light metaphor used in the design of the boards was helpful in differentiating the board types in a very rudimentary fashion. For example, P1 unloaded and organized all boards based on color and P3 automatically selected the battery board and an action board for their circuit design based on color differences. However, the semantic meaning of the colors was often not understood. P2 selected just a yellow and green board, and P5 selected two green boards to connect together. In those instances, we had to introduce the concept of a power board. As participants started to connect the three board types, we also had to introduce the traffic light analogy in relation to the circuit to improve their understanding.

7.3 Module Manipulations

All the participants were able to pick up the boards, hold and orient them without any assistance. Only P9, who had fine motor issues, slid the boards off the table and utilized both hands for holding and rotating the modules. The use of coin cell batteries proved problematic, with only about a third of the participants (P1, P3, P5) correctly inserting the batteries. Similarly, only three participants (P1, P4, P7) could operate the sliding switches without assistance. It was often pressed or rotated in the first attempt. Controls that required simple pointed motor actions such as the push-button, touch sensor, and reed switch were easy for all participants. However, potentiometers on the light mixer boards however had mixed results, with only three participants not requiring some form of support. Although we had used large knobs, they required reorientation or bracing in order to operate.

When participants faced issues with manipulating or controlling the modules, we worked with the support workers to provide either verbal, gestural, side-by-side demonstration, stabilization or hand-over-hand support (Figure 10). For example, a couple of moderate-support participants (P2, P3) required side-by-side demonstrations followed by gestural or verbal support before being able to remember how to manipulate sliding switches. Some other moderate to high support participants required assistance in stabilizing or holding the board vertically (P6, P9) while manipulating the controls.

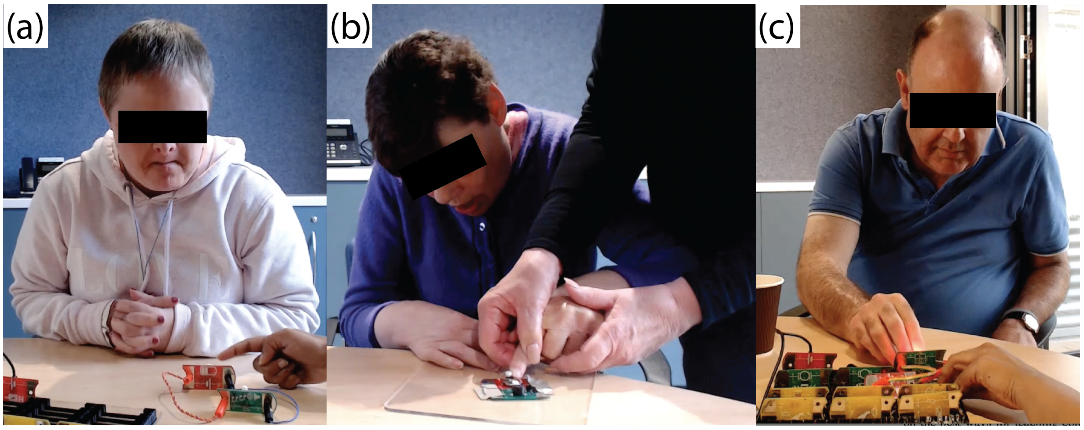

Figure 10: Participants receiving (a) gestural prompts, (b) hand-over-hand assistance and (c) stabilization assistance to help manipulate slide switch and rotary knob controls

We observed a pattern of slow progressive learning through repeated guidance, use and interaction. The three most elderly participants, for example, required hand-over-hand demonstrations multiple times throughout the study (Figure 10b) to accommodate their fine motor, motor planning, or memory issues. For P9, this progressive learning led to a non-standard circuit consisting of the battery and music board arranged back-to-back vertically to help her practice sliding (Figure 9a) due to her motor control issues.

7.4 Making Connections

Participants had the option to connect circuits using conductive tape, banana plugs, crocodile clips and conductive thread. Of the four options, only the first three were evaluated by all the participants. Only 5 low to moderate support participants tried conductive thread since it required considerable motor skill, time, and cognitive estimation capabilities (e.g., thread length).

Conductive tape was by far the most effective connector for many participants, but four participants (P2, P6, P8, P10) required our assistance with the scissors in creating connection strips. Users had no issues placing the tape on the pads, but they sometimes overlapped the IN and OUT terminals on the sensor boards or taped beyond the terminals. Conductive tape required the least stabilization but had the conceptual drawback of being mistaken for common tape. Consequently, some participants thought they were taping down individual boards to the clipboard rather than using it for electrical connections between boards.

Banana plugs were the most recognizable connector, given the appropriately sized holes in each board. Almost all participants (except P8) could infer where to plug the connector without any verbal or gestural assistance. The major issues were with alignment (2/10 participants), not fully plugging in the connector (4/10), and the pressure required for a successful connection (4/10). Banana plugs also required considerable stabilization of the boards, which we initially supported but was eventually accomplished by the 3D-printed stand as part of the kit. This outcome greatly improved individual agency for some of the participants.

Unlike the banana plugs, the crocodile clips were not constrained to a specific point in the terminals. However, only two participants (P1, P4) could successfully clip them to the boards. Nearly half the participants (P3, P4, P6, P7) tried passing the clips through the holes akin to banana plugs, and a majority (7/10) required hand-over-hand support to either orient the clip between the fingers or apply pressure or both. Participants could easily remove the clips from the boards in comparison to the other connection methods.

In making circuits, we mainly observed two types of board orderings. The majority of participants correctly arranged the boards vertically (as in Figure 3). Only a couple of participants (P8, P10) mated the concave and convex edges together as if trying to complete a puzzle. We witnessed users self-correcting to vertical alignment upon using the wired connectors. Only two participants (P2, P9) had both the correct color ordering and correct board orientations at their first attempt, when making sensor circuits. As alluded to earlier, the traffic light analogy for board order was only useful to a few.

7.5 Troubleshooting and Fixing

Participants required considerable assistance troubleshooting and fixing malfunctioning circuits. Although the participants could not figure out the associated errors, we tried to involve them in the troubleshooting and fixing process. We found that after a couple of collaborative fixes, a few participants could suggest some areas to check when they noticed a new malfunctioning circuit.

Common errors included overlapped conductive tape pieces bridging contact points (4/10 participants) or inner circuit components (5/10). While we explained and corrected the errors, some users supported us in removing and redoing the tape and provided verbal and gestural assistance. Those who faced these issues could often completely avoid or eventually reduce the occurrences of these errors in the subsequent circuits. Only a couple of participants (P7, P8) faced similar errors and required assistance more than 3 times.

The majority of participants did not utilize the use of indicator LEDs on boards during the troubleshooting process. This was particularly evident with the slide switch, which was sometimes slid only half way, preventing the status indicator from activating. Only P1 demonstrated the active usage of indicator LEDs to aid in the troubleshooting process. Other occurrences of malfunctioning circuits were rare and were due to either environmental conditions or damaged electronics items. We faced one issue where the light sensor was saturated by the bright overhead lights in the room and another with a damaged reed switch, but we fixed these errors by changing the sensor thresholds to suit the environment or replacing the damaged electronic part.

8 DISCUSSION

During the TronicBoards evaluation sessions, the participants actively engaged in circuit making activities, and demonstrated an ability to independently make decisions during certain tasks. However, even with the affordances (e.g., color-coding, icons on the back, board shapes) and support for motor issues (e.g., larger knobs, stabilizing stands, connector options) that we incorporated into the design, participants faced challenges during the circuit building process. Particularly, they had issues in comprehending and manipulating some toolkit items, affecting the circuit building and troubleshooting process. In this section, we discuss the implications of our work, particularly concerning accessible electronics and accessories, the trade-offs in foregrounding and backgrounding design elements, and designing for small wins.

8.1 Reducing Errors through Design

The frequent errors made by our participants highlight the need for careful consideration of design aspects in accessible electronics. For example, despite the high usage and interest, there was a higher rate of errors in conductive tape circuits due to the lack of boundaries in the board pads. Since defined holes worked well for guiding banana plugs, we suspect that a guided taping approach with raised borders could minimize these frequent errors. This would also minimize short circuits arising from conductive tape overlaps with inner parts of the circuit. We also witnessed participants having difficulty understanding certain boards such as tilt and reed switches. This may require new symbols and terminology, which could be developed by involving participants in subsequent iterations of the toolkit. We were encouraged by the different names participants recommended for the fan board. A high rate of single-point failure also occurred due to difficulties in comprehending and manipulating sliding switches in power boards. This could be reduced by replacing them with easier to manipulate toggle switches. Although the sliding switches on the action boards were also difficult, they were useful for building motor skills (as in Figure 9a) in some participants. Therefore, instead of replacing them, they could be further improved with start and stop markers and a slide-direction indicator. Overall, design attempts for minimizing errors and failures should not eliminate room for skill improvement.

8.2 Supportive Accessories to Scaffold Agency

We witnessed that the 3D printed stand that we initially used to store and display TronicBoards became an integral part of the kit for securing the boards during the connection making process and in operating controls like knobs and buttons. This finding highlights that the supportive accessories surrounding the kit can often play a crucial role in accommodating the special needs of people with intellectual disabilities. With respect to TronicBoards, this extends to the 3D-printed covers for various switches and controls; different shaped and sized covers could accommodate varying motor skills. For those who have difficulties cutting and separating the release paper from conductive tape, a custom-made tape dispenser with a "press to cut" approach would be helpful. Another accessory that we could provide is 3D printed puzzle-shaped enclosures for each of the modules, so that those who have difficulties in understanding the board connection order and direction can use them to learn-through-play [44]. Such templates can be introduced without the need for external connectors (as in [18]) or with in-built connectors (as in [23]), meaning that placing the boards in order would automatically make the connections. Although the latter option would make the modules easier to connect and reduce the overall amount of work, it may take away from the sense of accomplishment participants feel in completing slightly difficult physical interactions. These accessories could be suggested by support staff as needed in a context-sensitive manner depending on the needs of the user. More than electronic components, such accessories can play an important role in electronic toolkits for people with IDs, as they can provide customized support to enhance users' independence when needed; however, their design requires careful thought.

8.3 Trade-offs in Foregrounding and Backgrounding

TronicBoards was designed to support individuals within a wide spectrum of IDs. As such, our design included multiple ways to understand and take part in circuit building activities. However, in including and implementing all these design elements, we may have also made it confusing and overwhelming for some users. For example, the technical circuit symbols on the back of each board (aimed at long-term skill improvement) could be removed or backgrounded (in a lighter color) during initial introductions to the toolkit. More relevant icons could be foregrounded (through size or color) to draw attention to the functionality of the board. This also highlights the need to find better strategies to draw users' attention to tactile or visual cues that can support them the most. While we discovered that not all features that we included in the toolkit were relevant to everyone, the best ways to foreground and background the design elements depending on the user remains an open question.

8.4 Designing for Small Wins

Through the evaluation of TronicBoards, we realized that the design of electronic toolkits is not so much about successfully completing the circuit but about providing small wins during the process. Small wins could include identifying the correct board, determining the order of boards, actuating circuits or making connections. Such small wins increase a sense of agency in individuals with ID, and even in our study, we had individuals celebrating when they had accomplished each of these activities. For our participants, TronicBoards also acted as a platform that facilitated practice in certain skills through short-term involvement (e.g., progressively learning to slide a switch or to collaborate with the researcher in troubleshooting, identifying colors using a light mixer board). Sense of agency, associated enjoyment and opportunity for skill improvement can enhance self-reliance and mental health of people with IDs, which is one of its crucial benefits, given the limited opportunities they have [1, 24]. Ultimately, the goal is to have these small wins lead to personally meaningful and computationally rich artifacts, helping people with IDs move away from the common role of passive recipients of technology to active designers of technology.

9 LIMITATIONS AND FUTURE WORK

During our study, we observed that our participants were not highly verbal and sometimes demonstrated a willingness to please the researcher (e.g., indicating that they liked all connectors tried when the researcher asked for a preference). Therefore, we relied on interpretations of their gestures, facial expressions, social interactions and physical interactions with the toolkit. However, we tried to accommodate these limitations by having multiple researchers interpret the data and by using the techniques suggested by interaction analysis to neutralize researchers' preconceived notions and reduce the occurrence of ungrounded speculations. We also faced inconsistent study durations across evaluation sessions, as some participants could only work for short periods. As a result, not every participant was able to try all modules and connectors. This limitation could be overcome with a future study that deploys TronicBoards in the daily practice of people with IDs. This would also help us better understand the building of independent skills, making aspirations, and long-term benefits in support of our vision.

These long-term evaluations would also help us understand how the design choices embodied in the TronicBoards toolkit could potentially influence the types of digital artifacts made by people with IDs. For example, we could investigate whether and how TronicBoards affect people with IDs' (1) involvement in different phases of making [37], (e.g., wire connectors would suit quick prototyping in the creation phase, whereas conductive thread and tape would suit the final artifact creation in the usage phase), (2) feelings towards artifacts (e.g., whether their stronger attachments to artifacts prevent them from destructing artifacts and re-purposing components to achieve new goals) [37], (3) expressiveness in artifacts [35, 37], and (4) ability to achieve different goals (e.g., creative vs. technical artifacts, monolithic vs. distributed design) [35]. Future work can also aim to evaluate how/whether our findings can be generalized to other regions in the world and other disability communities, which has not been a focus of the present study.

10 CONCLUSION

In this paper, we presented the design and implementation an electronics toolkit; TronicBoards, to facilitate the benefits of electronics-based making for the marginalized group of people with intellectual disabilities. It also reported findings from one-on-one evaluation studies that we conducted with 10 people with a range of intellectual disabilities in the presence of disability support workers investigating participants' reactions to and interactions with TronicBoards. Our results suggest that circuit-making activities using TronicBoards facilitated enjoyment, a sense of agency, and opportunity for skill improvement, despite the time-to-time reliance on varying levels of assistance to comprehend and manipulate toolkit items and build and troubleshoot circuits. Based on evaluation results, we further provide implications for improving the individuals' independence and personally meaningful experiences within the toolkit.

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