Connectors in Maker Kits: *Investigating Children's Motor Abilities in Making*

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ABSTRACT

The study of Making to support children's cognitive or social needs is gaining prominence rapidly. However, little research in Making focuses on children's motor skills and abilities, especially at younger ages. Arguing that Making provides greater benefits when introduced at elementary school-aged, this paper contributes to the understanding of how children aged 8 to 11 manipulate connectors, a key component of Maker kits. We present a review of connectors used in prior work, a theoretical foundation based on the mediated action theory of affordances, and an empirical study of children using 6 different types of connectors with various affordances. Based on quantitative analysis and qualitative video analysis, we present themes that may guide the design of components in future Maker kits for children, with a view towards usability aligned with children's capabilities and mental models.

Author Keywords

Usability, Motor abilities, Connectors, Children, Maker kit, Making, Design, Evaluation

ACM Classification Keywords

H.5.2. User Interfaces: User-centered design

INTRODUCTION

Making has been defined as the “hands-on production of artifacts that are technologically-enhanced” [1]. Such activities are complex and entail a confluence of cognitive, kinesthetic, and perceptual-motor aspects. But even as research in children's Making gains momentum, most studies have focused on the cognitive aspect of the activity: learning (e.g., [2]), creativity (e.g., [3]), engagement (e.g., [4]), interest (e.g., [5]), identity (e.g., [6]), etc. Augmenting the intellect and higher-order thinking is admittedly a difficult enterprise and a critical goal of third-wave HCI [7]. Yet, engagement of cognition has to necessarily occur

through our bodies. It is only through our body and the senses that it affords us that we can interact with the world. For children especially, motor abilities sometimes defines what they can and cannot do, even before cognitive understanding.

Our work presents a direction of research in Making for children that looks closely at the physicality of Making, and how to design for it. In this paper, we focus on one critical component of Maker kits to explore the issue: connectors. Making electrical connections that are both electronically functional and structurally robust is a critical challenge in electronics. For this reason, many inventions (e.g., [8, 9]) for example in the domain of electrical engineering center around new connector designs. Whole companies (e.g., [10, 11]) have been established solely to provide connectors to engineers and Makers. Connectors are especially important in Maker technologies targeting children for two main reasons, one being that they can be particularly hard to use or implement for users without fully developed motor abilities, and the other being that they represent enormous learning opportunities for children to understand underlying electricity and STEM (Science, Technology, Engineering, and Mathematics) concepts.

We first review the literature on children's general motor development, and then work on Maker kits for children, focusing on prior types of connectors used. We then describe three new connector designs that we have developed, and describe a study with elementary school-aged children that sought to evaluate the different types of connectors that we found in children's Maker kits. We present our findings on the children's use and performance with the various connector designs, and discuss insights about the general design of Maker kits with respect to children's motor abilities that our design experience and study results put forth.

CHILDREN'S MOTOR ABILITIES IN MAKING

Motor skills are typically classified as either gross motor skills or fine motor skills. Although gross motor skills are important for handling large-scale equipment and materials, in Making for children, we are mostly interested in fine motor skills, “the use of small muscles involved in movements that require the functioning of the extremities to manipulate objects” [12]. Studies have shown that fine motor skills are heavily used at school [13, 14], particularly through the use of writing tools and other implements, and

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that they represent an influencing factor of immediate or later academic achievement [15, 16]. With the increasing introduction of Maker technologies into schools and other formal or informal learning contexts, the study of motor skills and physical requirements with respect to children's Making is lacking.

For typically developing children, motor skills are expected to be more or less fully developed by 10 years old. In a recent study of children aged 6 to 12, Gaul and Issartel [17] report that all the children, except for 2nd graders, performed below expected proficiency levels. They attribute the poor performance and the slow-down in the rate of development of motor skills to the new technological leisure environment of children nowadays, consisting of computer and media-based activities instead of the "traditional activities such as playing with blocks, Lego, board games or jigsaws". Much of the empirical research on children's motor abilities has been done with either writing or drawing as focus activity, given not only their importance in education, but also the high levels of eye-hand coordination, force regulation and precision that these activities require. Criteria for the evaluation of handwriting performance typically include 'product legibility' and 'writing speed' [18]. In drawing, aspects such as 'drawing duration', 'drawing velocity', and 'number of peaks in stroke velocity profile' are considered [19].

Making involves many physical components, a large part of them being small in size, such as resistors, diodes, wires, LEDs. Making also relies heavily on physical processes, e.g., soldering, plugging, twisting, positioning, sewing. The physical expertise required in electronics Making and crafting is highlighted by the results of Buechley and Perner-Wilson's [20] survey. Unfortunately, virtually no research can be found on how children's Making relate to physical and motor skills. A sub-area of children's Making that may be relevant is that of accessibility in digital fabrication or DIY-AT (Assistive Technology). But work in that area is as of now scarce and far from mature. Leduc-Mills et al. [21] and Wentz et al. [22] draw out the potential of appropriately-designed Maker technologies for children with disabilities, and through their interviews with non-professionals adapting AT for children, Hook et al. [23] describe the challenges therein, e.g., the difficulty of finding custom parts, the need for frequent repairs.

Most research results on Making activities do not report on the motor difficulties faced by the participating children. Among the exceptions, Weibert et al. [5] feature the concern and struggle of children using Making tools as a theme of their study findings observing children aged 8 to 12 engaging in e-textile activities with the LilyPad kit [24]. They state that "the handling of soldering irons and pliers turned out to be challenging for some." Further, they "observed both boys and girls struggling using physical artifacts, both in terms of handling delicate components and

using the tools of making". They point out that some children lacked hand strength and the size of the tools was so problematic that it led to the need for the children to receive extensive help.

In their workshop with middle school youths building game controllers with the MaKey MaKey kit, Davis et al. [25] informally reported that "several youths mentioned that they found working with the alligator clips challenging, because the holes on the MaKey MaKey were small and the clips were difficult to open." Our own experience of organizing many Maker activities for children, and working with and observing them through the process reinforced children have working with connectors.

THEORETICAL FOUNDATION

We look at the notion of affordances to ground our research on children's motor abilities in Making. While most agree on the usefulness of affordances to the design of tools and systems, as a concept has long been a subject of discussion and debate among HCI researchers. Various conceptualizations of affordances can be found in the literature [26-29]. We adopt Kaptelinin and Nardi's [30] 'mediated action' approach to affordances here. Their theory is grounded in Gibson's original concept of affordances from ecological psychology and informed by Vygotsky's [31] socio-cultural approach. For them, affordances are understood as "action possibilities offered to the actor by objects in the environment". Contrary to Gibson however, affordances occur between the person and tool(s) in a cultural environment. Perception of affordances can be the result of learning, and may be dependent on the user's situational needs.

Four kinds of affordances are distinguished in the mediated action approach: i) instrumental; ii) aggregation; iii) maintenance; and iv) learning. Instrumental affordances are those properties that characterize an object as an instrument through which the actor interacts or affects the environment. There are 2 subcomponents of instrumental affordances: a) handling affordances, that dictate how the object should be handled (e.g., handle of a knife); and b) effector affordances, that cause the actual effect (e.g., blade of a knife). Aggregation affordances refer to how the object may be combined with other objects. Maintenance affordances refer to how the object may be kept usable and up-to-date, and are not particularly relevant in our case. Learning affordances are properties that inform the user of how to go about using the tool.

Kaptelinin and Nardi's framework will be used to examine the affordances that a particular type of Maker kit component provides, and how these relate to the child's motor abilities. Specifically, in this paper we investigate connectors, a necessary component in Maker kits in terms of how children manipulate them, the challenges they face, and their perceptions of different types of connectors, with a view to inform the development of suitable Maker kit components.

CONNECTORS IN MAKER KITS

An electrical connector is usually a device that serves to connect two parts (a male and a female part) of an electrical circuit through mechanical assembly. There are hundreds of different types of connectors [32]. In this section we present a review of connectors that have been used in previous work on Making with children, including 3 of our own, and situate each type within the mediated action approach to affordances.

Common methods of electronic connection in electrical engineering typically consist of for instance, soldering, crimping, wire-wrapping, use of industrial adhesives, or connector assemblies. While some studies have reported having children use soldering and plier methods in Making activities (e.g., in the Bunny Bright project in Weibert et al. [5]), most recognize that these methods are either unsafe for children or beyond their motor skill.

The 2 prominent solutions to this challenge that we saw being used in Maker activities with children is the use of magnets and snapper connections. The ‘magnets’ solution employs conductive magnetic contacts to make connections. They have the advantage that by configuring magnetic polarities, the kits can ensure that only connections of the correct electrical polarities can be made. Wholesale Maker kits that use this technique include *Little Bits*, the modular *Circuit Scribe* [33] and *Light Up* [34]. One instantiation of the magnet connector that we built based on these principles is shown in Figure 1. We used a 3-element design: a $\frac{1}{4}$ " diameter steel washer, a $\frac{1}{4}$ " diameter circular magnet, and a 3D-printed housing shaped like a cap into which the magnet fits snugly so that it can be friction-fitted into the cap. The cap has 2 slots on either side for the wires. A connection is made by winding the wires around opposite sides of the washer, inserting the washer into the cap, and pushing the magnet into the cap on top of the washer. The magnet holds the wires together by sandwiching them between the washer and the magnet, and the cap provides mechanical strength so that the wires are not easily pulled apart. It takes eight minutes to 3D print the cap. The magnet and washer are commodity items that can be obtained from a crafts store and hardware store.

Kits that employ snappers include *Snap Circuits* [35] and derivative kits that

Figure 1. Magnet, snapper and alligator clip connectors

employ the clothing snap-button-like connectors. An instantiation of this type of connector that we built is shown in Figure 1. The snap connectors are constructed using standard snapper buttons commonly used in clothing/textiles. The difference between our use of snappers and those found in kits is that we isolate the connector from the electronic components while existing kits typically have the snapper integrated with modules that encapsulate the components. We attach the snappers to wires and component leads. The snapper connection requires assembly of 3 elements on each side of a connection. The button is usually crimped onto fabric with a ‘button part’ and a cap that has a stem that goes through a hole in the material. For the male side of the connection, we crimped the button directly onto the connecting wire by first wrapping the wire around the stem of the cap element. For the female side, we crimped the cap onto the female snapper element and soldered the wire to the assembly. It takes about 2 minutes of manual labor to construct each male-female connector pair.

Another commonly used connector that can be easily obtained is alligator clips. Cooney and Mueller [36], and Tadhg [37] report using them in their Making studies with children. Other types of connectors for children that have been tried relate to more arts and craft methods, for instance squishy circuits [38, 39] that use malleable conductive dough, conductive ink [3, 40] or conductive thread [41], and foil and copper tape on paper [42].

Over the course of 4 years, we have developed a series of 15 Maker kits for children to be used in different workshops and elementary school classroom sessions. These Maker kits were developed to support different activities, ranging from storytelling to learning about circuits, to science experiments [blinded ref]. Three connectors were designed by designers in our group for the Maker kits throughout our experiences: D-sub pins connectors, wedge connectors, and clamp connectors.

The *D-sub pins connectors* (Figure 2) are made using commercially-

Figure 2. D-Sub pin connector

available pins that are found, for example, in standard VGA connectors. We employ isolated pins that we solder and crimp onto wires. A piece of color-coded heat-shrink wrapping is applied to each D-sub pin and wire connection to protect the connection and to prevent short-circuits. Wires attached to a male and female D-sub pin pair constitutes a single connection that can be made. To make each side of the connection, we have to strip the wire, solder it to the pin, crimp the pin onto the insulator part of the wire, and apply the heat shrink. It takes about 2 minutes of manual labor to construct each side of the connector pair.

Wedge connectors (Figure 3) are designed to insert electronic components like resistors and capacitors into a circuit constructed by applying conductive copper tape to a

paper or card stock substrate. The wedge connector comprises two elements: the base and the component carriage. The base sits on the paper or card stock substrate. The copper tape runs from the substrate onto the ramps on each side of the base, and terminates in the carriage pit in the middle of the base (the copper tape from both sides must not meet in the carriage pit). The component is placed on the carriage, and its leads wrap around the sides of the carriage. Both the carriage and the carriage pit have matching corrugated ‘teeth’ to ensure a tight force fit. When the carriage is pushed into the carriage pit in the base, the leads of the component make firm contact with the copper tapes that run on the opposite sides of the carriage pit, making the electrical contact. The wedge component connector elements were designed in AutoCAD and printed using an Ultimaker 3D printer. It takes nine minutes to print the two elements and about 15 seconds of manual labor to clean them off. No other manufacturing steps are needed.

Figure 3. Wedge connector

Clamp connectors (Figure 4) are designed to connect 2 wires electrically and mechanically. It comprises two 3D printed elements: the wire carriage and the clamp. Both components are designed with matching corrugations to provide mechanical strength to the connection. A connection is made by wrapping the wires around the wire carriage and pushing the carriage into the clamp housing. A wedge feature on the housing forces the wires together in the channel in the middle of the carriage to ensure electrical contact. The 2 elements of the wire clamp takes a total of 10 minutes to print on an Ultimaker 3D printer, and the only manual labor required is the approximately 15 seconds to clean off the parts after printing.

Figure 4. Clamp connector

Analysing Connector Affordances

We use the mediated action approach to analyze the affordances of a set of the different types of connectors reviewed. Table 1 shows our analysis of the magnet, snapper, alligator clip, D-pins, wedge and clamp connector types with respect to handling and effector instrumental affordances, aggregation affordances, and learning affordances. Despite having the same function of bridging two parts of a circuit, each of the connectors has different characteristics in terms of shape, size, number of units, feel, familiarity, etc. We can expect that children would respond to each one differently, and display different interactional abilities for each in building circuits.

STUDY DESCRIPTION

We conducted a study that sought to contribute to our understanding of children’s motor abilities with respect to connectors in Making. Specifically, our research questions were as follows:

- How do elementary-school aged children manipulate connectors with different affordances?
- What physical challenges do connectors with different affordances present to elementary school-aged children?
- What are elementary school-aged children’s perceptions of connectors with different affordances in terms of usability?

The study was carried out with 18 children (12 boys, 6 girls), aged 7 to 11, in the form of an electronics-based scavenger hunt, whereby children had to build circuits using different components from station to station. Recruitment was done through an open call to the university listserv. Interested parents registered their children by emailing or calling a researcher, and were assigned a time and day to bring their child to participate in the scavenger hunt. Three sessions of the hunt were organized over 3 different days, with each session having 5 to 6 children. A session lasted around 1.5 hours, and all sessions of the study were audio and video recorded.

The 6 connectors listed in Table 1, with their wide-ranging affordances, were used as subjects of investigation. The hunt consisted of 6 stations (one for each connector type) spread across 3 connected buildings. Each station contained materials for 2 basic LED (one blue and one red) circuits with a different type of connector, a sample completed circuit with the respective connector, a riddle, an associated

Table 1. Connector affordances

Connector	Instrumental Affordances		Aggregation	Learning
	Handling	Effector		
Magnets	Consists of multiple units (magnet, washer, cap)	Magnet snaps to washer when within range	Circular designs recurrent across all units	Requires knowledge of magnetism
Snappers	Small, circular Snap buttons	Buttons need to be snapped into each other	Buttons have same metallic attributes	Draws from familiarity with snap buttons
Alligator clips	Covered clips	Clips need to be pressed open and hooked onto each other	Both recipients have same designs	Relies on prior encounters
D-Pins	Long, thin wires	One end has to be inserted into the other	Pointed end and recipient tube	Relies on physical properties
Wedge	Triangular cap with hollow wedge	Triangular cap needs to be pushed into wedge	Cap and wedge shapes aligned with corresponding teeth	Relies on physical properties
Clamp	Long, thin wires wrapped around a tuxedo-shaped piece, with a cap	Tuxedo-shaped piece with wire needs to be capped	Corresponding side teeth and grooves on each piece, with direction of wire coming out	Relies on physical properties

sticker reward, and ASQ forms (see protocol). Figure 5 shows a station setup. The children's task was to go to each station, make up the 2 circuits, and use the LEDs to provide the correct answer to the station riddle in Morse code to a helper. They do so by lighting the blue and red LEDs on and off as appropriate to match the code letters of the correct answer. If the children transmitted the correct Morse code to the helper, they receive the sticker reward and can move to the next station. Else, they are asked a different riddle until they provided a correct answer. The protocol of a study session was as follows:

Figure 5. Station setup

1) Registration: The parents and children were brought to a waiting area upon arrival. The parents were given an information sheet, and asked to sign a consent form;

2) Briefing: All participating children were moved to a common area, where a researcher introduced the study and did a presentation on i) how to use Morse code; ii) a basic LED circuit with a switch; and iii) a quick overview of the 6 types of connectors that they were going to use on the hunt. The children were given the opportunity to ask any questions about the different connectors. They were then paired, and each pair was given a packet containing an order list of the 6 stations, a map of where each station was located, and an empty sticker reward sheet. Figure 6A shows a child arriving at a station with her stations map;

3) The hunt: All children pairs were then sent off to do the hunt, with a helper attached to each pair to ensure that the children could find their way around and to provide assistance if problems occurred during circuit construction. The order list of stations of each pair was randomized. Each child had to build a circuit at each station ((Figure 6B), one child making the red LED circuit and the other the blue LED circuit. Help was given to a child if requested (Figure 6C), or if the child was observed to struggle exceedingly, but helpers were instructed to give full independence to the children in circuit construction as far as possible. After successfully answering a riddle in Morse code (Figure 6D) and before he/she received the reward sticker for a station, each child in the pair was asked to fill in the IBM's 'After-Scenario Questionnaire (ASQ)' [43] for the particular connector that he/she just used. The ASQ consists of 3 simple statements that we adapted for children to be: i) I am satisfied with the time it took to complete this task; ii) I feel

I can do this task by myself; and iii) I like this task. We provided children with 5-point Likert scale smiley faces (the smileyometer [44]) to record their answers.

4) Post-questionnaire: When a pair had either obtained all 6 station reward stickers, or at the end of an hour, the children pair was brought back to a common area. Each child was then asked to fill in an adapted version of the IBM's 'Post-Study System Usability Questionnaire (PSSUQ)' for each connector, with a pictorial representation given for reference. We removed statements that did not apply to our task (e.g., "The organization of information on the system screens was clear."), and had 10 questions pertaining to ease and comfort of use, effectiveness, speed of construction and use, ease of understanding, of learning, and of fixing errors, amount of help needed, and general likeability for each of the 6 connectors.

5) Debriefing: After questionnaire completion, the children were asked to cast a vote for their favorite connector. They were then each given a gift bag, and brought back to their parents.

DATA ANALYSIS

All questionnaire data were entered into a spreadsheet and a statistical analysis program. Averages were calculated for each of the 3 ASQ statements across all participants for each of the 6 connectors. Scores for the 10 statements in the PSSUQ were averaged to obtain one 'usability score' for each participant per connector. Repeated measures (univariate) ANOVA tests were performed to compare the effect of connector type on: i) post-task usability (ASQ) scores; ii) post-study (PSSUQ) scores; and iii) amount of time taken to complete a connection.

A total of 18 hours of video recordings were collected. After cleaning up irrelevant parts of the video, 8hrs dealing specifically with the study were subjected to a first level of coding. We isolated the parts of the recordings that showed the children actively engaged in circuit construction at each station. A pair of

Figure 6. Study pictures

children took 8 minutes on average at one station. From the video, several variables were extracted: a) *Connector completion time* – the total time taken for each child to complete a connection using each connector was tracked. Time in the process of construction when the child was not actively focused and working on the task was excluded (e.g., distracted by someone entering the room, or talking to helper on unrelated subject); b) *Attempts* – the number of times that the child stopped and re-attempted to complete the connection; and c) *Success/Failure* – whether the child ultimately succeeds or fails to complete the connection using the connector. These variables obtained from the video analysis were also entered into a statistical analysis program, and descriptive statistics were run.

A process of qualitative coding [45] was then performed by two researchers on the video for selected children for each connector as follows: 1) The videos of 2 children of ages 8, 2 of ages 9, 1 of age 10 and 1 of age 11 were selected for in-depth analysis; 2) Coding was performed on the video to identify instances when the child *received help or guidance*, whether solicited or unsolicited, during the use of the connector, as well as instances when the child *encountered problems or challenges* while using the connector; 3) Coding of the child's performance on each connector was rated using the *Manual Ability Classification System* (MACS) [46]. Each connector use instance was assigned a level based on observations of the child's behavioral interactions with the connector.

The MACS was developed to classify “how children with cerebral palsy use their hands when handling objects in daily activities”. It has been tested and scientifically validated with children between the ages of 4 and 18. MACS consists of 5 levels, with each level distinguishing a particular level of difficulty in handling objects. For example, an instance coded as level I in MACS would indicate that the child handles the object “easily and successfully”, showcasing “At most, limitations in the ease of performing manual tasks requiring speed and accuracy”. A level II in MACS would indicate that the child handles the object, but “with somewhat reduced quality and/or speed of achievement”, characterized by perhaps alternative ways of performance, and requirement of help to setup the activity. A level V in MACS, however, would indicate that the child cannot handle the object, and has severely limited ability to perform the required actions. This would be evident through the need for continuous assistance or help.

Several other frameworks exist to assess motor abilities, e.g., the Peabody Developmental Fine Motor Scales [47], the Quality of Upper Extremity Skills Test (QUEST) [48], Fine Motor Composite of the BOT-2, the Nine-hole Peg Test [49], or the Movement Assessment Battery for Children (MABC-2) [50]. However, we chose to use the MACS to code the children's connector use videos because it has been tested with children in our target age group, it enables coding of existing data (i.e., does not require

separate tests with other objects, e.g, pegs), and its emphasis is on the handling of objects “in an individual's personal space, the space immediately close to one's body” [46].

STUDY FINDINGS

Self-reported data

A. Post-task usability scores: ASQ

No significant differences were found in terms of the post-task usability scores, as measured by the ASQ. For the sake of understanding the trends however, Figure 7 still presents the means of the scores.

Figure 7. Post-task ASQ score means

Figure 8. Post-study PSSUQ score means

Figure 9. Average connector completion time

B. Post-study usability scores: PSSUQ

There was a statistically significant difference in the post-study usability scores (PSSUQ) based on the type of connector, $F(5, 81) = 8.22, p < .0005$, partial $\eta^2 = .34$. Post-hoc tests showed that clamps and magnets formed one subset A; magnets, D-sub pins, wedges, and snappers formed subset B; and D-sub pins, wedges, snappers and alligator clips formed subset C. Figure 8 shows the means of the PSSUQ scores.

Objective video coding

A. Connector completion time

There was a statistically significant difference in connector completion time based on the type of connector, $F(5, 85) = 21.12, p < .0005$; partial $\eta^2 = .55$. Post-hoc tests showed that D-sub pins, snappers and alligator clips form subset A, and clamps, wedges and magnets form subset B.

B. Attempts and Success/Failure

Not many re-attempts were found across all the children. Therefore we only report descriptive statistics for this variable. An attempt is defined here by a full disengagement and re-engagement, thus could consist of multiple rapid connecting and disconnecting of connectors. Among all children, no second attempts were done for the D-sub pin, snappers, and wedges connections. Five re-attempts were done for the magnet connector, 4 for the clamp connector, and 1 for the alligator clips. In terms of final success, 100% of the children eventually completed the alligator clips and snappers connections. Ninety percent of the children completed the wedge connections (i.e., some children gave up on their first attempt), 86.7% completed the D-sub pins connections, 83.3% the magnet connections, and only 54.6% completed the clamp connections.

Qualitative coding

A. Problems/challenges encountered

The problems encountered with the **alligator clips** were 2-fold: i) many children had difficulty either pressing the clips to open the teeth up, or maintaining them open long enough to make the connection with another alligator clip. This was caused by 2 main factors, first being the amount of force needed to press the clip open, and second the slippery feel of the rubber insulation covering the alligator clips; and ii) children were at times confused by the colors of the alligator clip rubber insulation. They insisted in requiring a red clip to connect to another red clip, and did not see the possibility of a green one to a red one.

Snappers led to 2 problems as well: 1) children did not have the necessary strength to snap the button together, leading to behaviors such as standing up straight and pressing down using the whole body weight (e.g., Figure 10-I); and ii) some children did not understand how to use the connector from its physical properties and affordances,

i.e., they failed to recognize the connector to be a snap button, until they were told.

Children faced 3 major problems with the **clamps** connector: i) they had difficulty aligning the teeth of the tuxedo-shaped piece (male side) with the teeth of the cap (female side) while at the same time as snapping them together. This resulted in them having to bring up the connector very close to maintain focus, either by bending or kneeling down (Figure 10-II) or by lifting it up to their chest (Figure 10-III); ii) Successful connection happened mostly when the connectors were rested on a flat surface, as opposed to free-standing in the hands, since the wires tended to slip from the tuxedo-shaped piece if they were not wrapped properly; and iii) children did not understand which piece was the male and which one was the female sides.

Two main problems were found with the **magnets**: i) the strength of the magnet required dexterity to manipulate, as it had to be placed at the correct distance from the washer and released with the correct timing to snap into the cap. If it was placed too close, the washer would come up to the magnet instead of the magnet snapping into the cap; and ii) children wrapped the insulated part of the wire around the washer, instead of only the stripped part of the wire, which allowed for the connection with the metallic washer.

The children completed the **wedges** connection without any observable challenges. The only problem occurred when they did not understand where or how to stick the copper tape on the base component (the male component).

D-sub pins connectors brought about 2 challenges: i) the small and thin size of the pin required focus from the children to align and insert into the male part. This was evident from the children sometimes slowing down during the process, bringing up the connectors close to the face, or biting their lips in concentration; and ii) the connectors slid off rather easily while the children constructed the rest of the circuit after completion of the connection. This was more obvious with this connector as it did not have any form of locking mechanism.

B. Instances when help was received

Since the children were allowed to

Figure 10. Behaviors during connection completion

act rather independently during the study, only 12 cases were found when the helper actually stepped in to provide hands-on help to the child to complete the connection. Help was needed for the wedges and clamp connectors, and alligator clips, and to a lesser extent the magnets connector. No help instances were found for the D-sub pins.

At a broader level, 5 main types of help were found to have been needed: i) the helper helped the child to apply force and pressure, e.g., for the snappers connectors, alligator clips; ii) the helper assisted the child in holding certain

Table 2. MACS scores

Gender	Age	Alligator clip	Snappers	Clamps	Magnets	Wedges	D-sub pins
Female	8	2	1	4	2	2	1
Male	8	1	4	3	1	2	1
Male	9	2	1	4	2	1	1
Male	9	1	1	4	1	1	1
Female	10	2	1	3	2	2	2
Female	11	1	1	3	1	1	1

pieces, e.g. for the magnet and clamp connectors that consisted of multiple components; iii) the helper aligned the component while the child did the actual connection, e.g., for the clamp and magnet connectors; iv) the helper either gave verbal instruction of what to do next, or provided guidance using the model circuit at the station; and v) the helper performed the task for the child while the child observes.

C. MACS assessment

The MACS assessment was performed based on an in-depth video coding of 6 selected children representing the various age levels in our study. Table 2 shows the MACS scores given by evaluators after discussion.

For **alligator clips** connectors, all children received either a 1 or a 2. The scores of 2 were when the child used alternative means to open the clip, for instance, pressing it against their chest or against the table surface.

For the **snappers**, all children analyzed received a 1, except for one 8-year old boy, who received a 4. A score of 1 is described as handling the object easily and successfully, with few limitations in performing manual abilities. These children recognized the ‘button’ characteristic of the snappers immediately and knew what to do. At most, they had to use the palm or body weight to apply additional pressure to perform the connection. A score of 4 is characterized by handling a limited selection of easily managed parts of the object with effort and with limited success, and requiring continuous support. The 8-year-old boy first tried to press the snappers simply using the fingers. After failing, he pressed the snappers to his chest, but still failed. He then used the table as a surface to press against to snap the buttons, and subsequently gave up after not succeeding.

For **clamps** connectors, all children received either a 3 or a 4. A score of 3 is described as handling objects with difficulty, and needing help to do the activities. A score of 4 has the same characteristic as a score of 3, but continuous support or assistance is needed for even partial performance in the task. An example scenario of a score of 3 would be the child managing to assemble all the parts independently, but eventually requesting help from the helper to hold the wire-wrapped tuxedo-shaped component in place while she pushed the cap in. An example case of a 4 would be the child needing to be told how to assemble the connector, requiring help to wrap the wire around the tuxedo-shaped component, and needing the helper to snap in the cap in his or her place.

For **magnets** connectors, all children received either a 1 or a 2. A typical score of 1 for magnets would be characterized by fluent wrapping of the wire around the washer, insertion into the cap, and snapping the magnet. A score of 2 would be marked by some slowing down specifically in the process of wrapping the wire around the washer, and the use of additional body weight (e.g., the hand palm) to press the magnet down into the cap.

For **wedges** connectors, the children received either a 1 or a 2. The scores of 2 were typically because the child needed guidance on when, how and where to place the copper tape on the base connector component.

For **D-sub pins** connectors, all children received a 1, except for the 10-year old girl. In fact, after completing the connections, one child commented that “this is too easy, I think I did it wrong”. The score of 2 was portrayed by a significant slowing down in the process of sliding the female part into the male receptacle tube, due to the need to align the 2 parts.

DISCUSSION

Chu et al. [6] have made the argument that Making should be incorporated into children’s experiences as early as elementary school. The goal of this research was to contribute an understanding of how children relate to Maker components with different physical affordances relative to their motor abilities and skills at this period of development of late childhood by focusing on connectors as an exemplar component of Maker kits. However, we have found that misuse of connectors often occurred as well as a result of a faulty mental model [51] of the connector type.

Our research questions dealt with 3 key questions of how children manipulate the connectors with different types of affordances, what are the challenges faced, and how the children perceived the different connector types. From both our quantitative and qualitative results, it is apparent that although each connector had its own advantages and disadvantages, the alligator clips, snappers and D-sub pins were the most usable and aligned with children’s abilities. The alligator clips and snappers benefitted greatly from children’s prior familiarity with such objects. The D-sub

pins had very clear male and female part affordances – only one thing could be done with each component, that is sliding one into the other. The wedges and the magnets connectors were more problematic, and the clamps were unsuitable for use by children. Wedges led mostly to a failure in understanding of the use of the copper tape for connection, and the magnets and clamps had too many parts for the child to handle, among other problems.

We abstract out themes that may guide the development of “developmentally-situated” [52] components for future Maker kits for children by relating our results with the general affordances of each connector type, as highlighted in Table 1 before.

Factors that may affect how children manipulate Making components include:

- The number of components needed to be handled simultaneously
- The number of simultaneous actions needed to complete the task
- The degree of explicitness of the visual and manipulative affordances of each component
- The degree of understanding of the science (e.g., wires, magnets, washers, copper tape all conduct)
- Mechanisms for implementing, disassembling but also to maintain the assembly
- The extent of object manipulation knowledge (e.g., fitting in small components is facilitated by anchoring one’s arms on a surface)

Thus, failures to successfully use the connectors were due mainly to either A. the child knows how to use it, but could not do it because of motor abilities, e.g., hard to snap; or B. the child could not figure out how to use it in the first place, e.g., how to open the alligator clips.

Challenges faced were caused by at least 3 overall dimensions:

- *Surface-level visual attributes*: color, size, shape, etc.
- *Texture attributes*: feel, etc.
- *Mechanics*: force/pressure, alignment/precision, distance, timing, etc.

Children’s self-reports were generally in line with our objective and qualitative video analysis. That is, affect (e.g., I like this task) towards the different types of connectors were more or less guided by the usability of the connectors with respect to their own abilities. The only exception was the magnets, which were perceived as fun because of its playful quality.

We acknowledge that our study was limited in terms of sample size and types of connectors evaluated. Although we chose a set of connectors with varied affordances, it is likely that other types of components may generate other themes and guiding factors for the design of Maker kit components for children. Our work however provides some

much-needed awareness and design insights into children’s needs and abilities more from a physical and motoric standpoint. To borrow a quote from a children’s makerspace manager who we talked to, “children are made to solder, and sometimes they get burnt, but it’s ok. They learn to do it properly the next time.”

CONCLUSION

A fair amount of research has been done on the cognitive needs and potential of Maker kits for children, but little serious attention has been paid to the motor abilities of children with respect to Making. Mostly, only anecdotal reports can be found about problems with physical aspects of interaction with Making components by children. In our work, we focus on connectors, an essential part of Maker kits. We present a review of the literature on connectors, analyze affordances of different connector types based on the mediated action approach, and conducted an empirical study with elementary school-aged children to understand how they would use the different connectors. From our results, we presented themes that may be used to guide future development of parts for children’s Maker kits.

SELECTION AND PARTICIPATION OF CHILDREN

Interested parents registered their children for the study through a recruitment announcement posted on university listservs. The parents were sent an information sheet and a consent form that they signed and returned to confirm their child’s study participation. They had the opportunity to ask any questions before consenting. On the day of the study, a researcher read a minor’s assent form to each child upon arrival, making sure that the child understood he/she was participating in a study and could quit at any time. Verbal assent was noted from the children. The study was run in a lab on the campus of a major public research university. Children who participated were from the area and mostly of higher socioeconomic status.

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