

MakerWear: A Tangible Approach to Interactive Wearable Creation for Children

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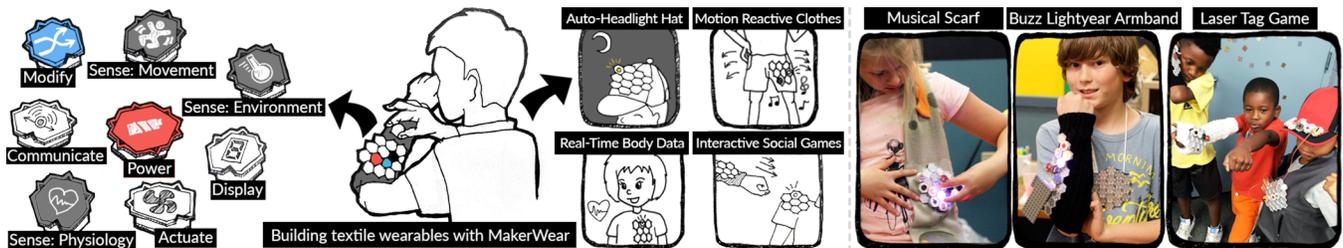


Figure 1: We introduce *MakerWear*, a new wearable construction kit for young children (K-6). By combining tangible, ‘plug-and-play’ electronic modules on a textile-integrated socket mesh, children can create a wide range of wearable designs from sound reactive clothes to interactive social games.

ABSTRACT

Wearable construction toolkits have shown promise in broadening participation in computing and empowering users to create personally meaningful computational designs. However, these kits present a high barrier of entry for some users, particularly young children (K-6). In this paper, we introduce *MakerWear*, a new wearable construction kit for children that uses a tangible, modular approach to wearable creation. We describe our participatory design process, the iterative development of *MakerWear*, and results from single- and multi-session workshops with 32 children (ages 5-12; $M=8.3$ years). Our findings reveal *how* children engage in wearable design, *what* they make (and want to make), and *what* challenges they face. As a secondary analysis, we also explore age-related differences.

Author Keywords

Construction kits; e-textiles; wearables; children; STEM

ACM Classification Keywords

H.5.2. User Interfaces – prototyping, user-centered design; K.3 Computers and education

INTRODUCTION

Wearable construction kits such as *LilyPad* [10], *Flora* [3], and *EduWear* [29] have shown promise in attracting underrepresented groups to STEM [13], expanding perceptions of computing [28], and empowering users to create self-expressive and personally meaningful computational designs [25]. These kits, however, require programming, an understanding of circuits, and manual skills like sewing and soldering. Though this complexity

allows users to create diverse and increasingly sophisticated designs—fitting Resnick and Silverman’s notion of “wide walls” and “high ceilings” [47]—it also presents significant challenges to young children and can impede playful experimentation and rapid prototyping (echoing [18,24]).

In this paper, we introduce and examine *MakerWear*, a new wearable construction kit for young children (K-6) that uses a tangible, ‘plug-and-play’ approach to wearable creation. *MakerWear* is comprised of two parts: (i) single-function, electronic modules that, when combined, create complex interactive behaviors, and (ii) a flexible, magnetic socket mesh that is either pre-integrated into clothing or attached *post-hoc* like a fabric patch. The mesh provides power, a communication infrastructure, and an easy method to attach and remove modules. By manipulating these tangible modules, children can create a wide range of designs, such as: a ‘*sound-reactive shirt*’ that changes color with music, a ‘*fitness tracker*’ that automatically counts and displays steps, or a new game of ‘*laser tag*’ where children interact together through their designs (Figure 1).

MakerWear is informed and inspired by prior work in digital-physical construction kits [58,59] and robotic kits [6,20] that demonstrate how, with appropriately designed tools, young children can develop basic programs and work with electronic sensors and actuators. Wearables, however, present a fundamentally different creative design context. First, constructions are *worn* and, thus, are inherently social, mobile, and potentially always with the child. Second, the focus of design shifts from electro-mechanical objects to designing for the *self*—children can create designs that react to their movement, physiology, and changing environment. Third, wearable creation pushes computational design outward from the confines of a room or a screen into the context of a child’s everyday life (e.g., pretend play, sports). Thus, we see *MakerWear* not just as a platform for creativity

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and self-expression but as a way for children to augment meaningful experiences in their lives with computation.

To build MakerWear, we pursued a two-year iterative design process, beginning with participatory design sessions with children, design probe sessions with STEM educators, and iteratively building and pilot testing prototypes with target users. Informed by these experiences, we built our final prototype with a focus on enabling children to leverage the richness of *wearability*—their changing environments, their bodies (e.g., movement, physiology), and social interactions. To examine *what* and *how* children make with MakerWear, what challenges arise, and how (and if) children leverage the unique properties of wearability in their designs, we conducted two single-session and three four-session workshops with 32 children (ages 5-12; $M=8.3$ years). Our findings show how children of all ages were able to build interactive wearable designs and develop understanding of key MakerWear principles (e.g., input/output, sensing, sequencing). The multi-session workshops allowed children to work on their own self-directed projects, which resulted in a broad set of creative designs from fitness trackers to superhero costumes.

In summary, our contributions include: (i) the MakerWear system, including the ‘plug-and-play’ modules and custom socket design, which dramatically lowers barriers to wearable design; (ii) findings from pilot studies and single- and multi-session workshops characterizing how children engage in wearable design, what they make, and the challenges therein; and (iii) an analysis of age-related differences in MakerWear creation and understanding.

RELATED WORK

We draw on two primary sources to inform our designs: (i) developmental psychology and early childhood education (e.g., [14,42,51]) and (ii) programming tools and creative construction kits for younger children (K-6). We also position our contributions within wearable design tools.

Theoretical Underpinnings

At roughly kindergarten age, there is a well-documented shift in cognitive and physical abilities [56]. Children demonstrate increased attention, self-direction, and logical thinking. Hand and finger control also improves, leading to greater enjoyment of and involvement with fine-motor activities [56]. These children are in what Piaget termed the *preoperational stage* [42,51]. They begin to think symbolically but struggle with abstract concepts like perspective-taking and mental modeling, so often need to rely on *physical representations* to help formulate, test, and revise ideas about how the world works [1,42,53]. By around age 7, children enter the *concrete operational stage*, characterized by the development of logical thought [42,51], but still primarily limited to concrete events or objects rather than abstract ideas. Thus, in our work, we take a *tangible* approach where wearable designs are built and ‘programmed’ using physical digital manipulatives [45].

Our work is also rooted in Papert’s theory of constructionism, which suggests that the best learning experiences occur when children are actively engaged in designing and creating things [27,40]. Constructionism places a critical focus not just on learning through making but on the *social nature* of design—that is, that ideas are shaped by the knowledge of an audience and the feedback provided by others [27]. As an outward facing medium, wearables are uniquely social compared to the more insular contexts of other construction kits, presenting opportunities for diverse feedback across social spheres from peers and parents to teachers and coaches. MakerWear also explicitly supports building social interaction through module behaviors (e.g., sending data to other wearers). Finally, Papert stresses that intellectual engagement is heightened when children work on activities and projects that are personally meaningful and interesting [47]. Our work begins to examine how children, enabled by our toolkit, engage with computational design to augment meaningful experiences and objects in their daily life (e.g., sports, pretend play).

Programming Tools and Construction Kits

A broad set of work exists on building and studying programming tools for children (see reviews [7,33]) though only a small subset is aimed at and evaluated with elementary-age children [43], our target group. For these younger users, two approaches are common: (i) simplified graphical, block-based user interfaces like *Scratch Jr.* [16,54] and *KidSim* [44,52] and (ii) tangible approaches that use physical manipulatives such as *Tern* [21] or *Strawbies* [22]. For either approach, tool designers attempt to reduce literacy and fine-motor requirements (e.g., typing, mouse input), simplify programming constructs (e.g., eliminate variables), and enforce syntactically correct programming statements through block-shaped constraints—compare *Scratch Jr.* (ages 5-7) vs. *Scratch* (ages 8+) [48], for example.

Our work takes a tangible approach. Tangibles can provide sensory engagement for young children [60], an easy entry-point for novices [53], visibility and concreteness of work [5], and opportunities for peer collaboration [21]. MakerWear builds on work in digital-physical, tangible construction kits, such as *Electronic Blocks* [58,59], *roBlocks/Cubelets* [36,49] and *littleBits* [4,35], where the entire programming experience—both user *input* and *output*—is tangible, without the need for a computer. Despite the popularity of these kits, we could find no empirical examinations with our target age range. One exception is *Electronic Blocks* (for ages 4-8): two qualitative studies showed that children could build structures with *sensor* and *action* blocks but struggled with *logic* blocks and sequencing. No direct comparisons across ages were made. Though not a purely tangible approach, Marina Bers’ extensive work with children (ages 4-7) and robotics also demonstrates that with proper instruction and tools, young children can build and program simple digital-physical constructions, though they struggle with looping, variables, and conditional statements [5,6,30,53,55].

In summary, while not aimed at wearable design, the above studies and tools help demonstrate that even the youngest users in our target range (ages 5-6) are capable of basic programming and working with sensors and actuators. We extend these findings to the context of wearable design.

Wearable Construction Kits

As noted in the Introduction, wearable construction kits such as *LilyPad* [10,13] and *Flora* [2,3] have helped broaden participation in wearable creation but still have high barriers to entry for children. Other wearable toolkits—*Quilt Snaps* [12], *EduWear* [29], *TeeBoard* [37], *i*Catch* [38,39], and *fabrickit* [15]—attempt to address some of these issues but are still designed for older children (10+) or adult hobbyists and, consequently, do not provide developmentally appropriate interfaces or architectures for younger ages. For example, *EduWear* (for ages 10-14) consists of a small set of pre-made fabric modules and a graphical programming interface for Arduino, but is otherwise similar to *LilyPad*—it requires sewing, creating circuits, understanding analog and digital I/O, and software programming to build even the simplest designs. *MakerWear* uses higher-order abstractions with a focus on *behaviors* (e.g., sensing motion, turning on a light) rather than circuits, low-level I/O, and writing code. Moreover, the mesh sockets eliminate the need for sewing.

Closest to our work is *i*Catch* (for ages 10+), which uses specially designed e-textile clothing with integrated wiring (“host substructure”) that interfaces with electronic modules via conductive snap fasteners. While *i*Catch* eliminates the need for some craft and engineering skills, the approach is still fundamentally *software* driven and requires writing code. Indeed, each of the aforementioned kits attempt to simplify aspects of building wearables but all use a conventional embedded systems model: a one-microcontroller-to-many-peripherals approach that requires interfacing with a computer to write, compile, and download code. In contrast, our approach allows children to build a range of wearable designs *tangibly* by manipulating plug-and-play modules. When a module is placed, creations work instantly to better support tinkering and rapid iteration.

DESIGN PROCESS AND GOALS

To design and build *MakerWear*, we employed an iterative, human-centered design process that included participatory design activities with children and design probe sessions with STEM educators. We then conducted lab-based and museum-based pilot studies with increasingly refined prototypes before deploying and studying our final prototype in single- and multi-session workshops. Here, we describe the initial participatory process and resulting design goals.

Participatory Design with Children

To gather design ideas and solicit critical feedback, we conducted five participatory design sessions with children. We employed a participatory design method called *Cooperative Inquiry* (CI), where adults and children collaboratively brainstorm, design, develop, and test technology [17]. The sessions spanned the design process,

from early ideation and lo-fi prototyping to using and critiquing functional prototypes. In total, 11 children participated (6 female) with an average age of 9.2 (*range*=6-11). Each session included 6-9 children and 3-5 adult co-designers; 8 children participated in more than one session ($M=2.9$ sessions/child).

In the two initial CI sessions, children used low-tech prototyping materials to design and sketch their own interactive clothing and wearable modules. Several recurring themes emerged: (i) reacting to body movement and physical actions; (ii) using the wearer’s physiology; (iii) designing custom-built games; (iv) appropriating clothing as a social communication device; and (v) pragmatic designs (e.g., increasing visibility at night for safety). In addition, groups wanted the ability to program their clothing to add new functionality (e.g., using Scratch), combine sensor modules to create custom inputs, and activate multiple output modules simultaneously. In later CI sessions, children helped test initial, semi-functional prototypes, pilot test design activities, and informally use and compare *MakerWear* to other construction kits like *Cubelets* and *littleBits*. From these sessions, children suggested new module types, larger socket meshes, and a greater diversity of clothes. Children also helped co-design the look-and-feel of modules (e.g., changing names like *UV Light Sensor* to *Sunlight Detector*).

Design Probe with STEM Educators

Once we had created initial, semi-functional prototypes, we solicited feedback from two groups of professional STEM educators: staff from an interactive children’s museum ($N=4$) and a STEM education consultancy ($N=8$). These sessions lasted roughly 90 minutes and included an introduction, a semi-structured interview about educational experiences and making philosophies, a demonstration of the current prototype, and, finally, a brainstorm session focused on eliciting design ideas and workshop activities. Both groups of educators were generally positive about our prototypes, particularly the ‘plug-and-play’ and tinkerability aspects, the use of wearables as a design platform (e.g., to support movement-based design experiences), and our use of iconography and color to distinguish the module types. They also suggested ideas for new modules, physical designs, and design activities, such as integrating lo-fi materials and trying to design for universal accessibility. Key concerns included: (i) the *learnability* of modules; (ii) the small *size* of modules, especially for younger children’s (ages 4-5) fine motor abilities; (iii) the *robustness* of modules, particularly when involved in vigorous activity like running or jumping.

Wearable Toolkit Design Principles and Goals

Informed by our participatory design sessions, our own experiences building, using, and testing initial prototypes (including early systems [31,32]), and relevant prior work (e.g., [16,47,58]), we synthesized the following key goals for a wearable toolkit aimed at children:

- **Leverage wearability.** Previous wearable toolkits provide basic components largely undifferentiated from robotic kits (e.g., light sensors, LEDs, speakers). In contrast, we aim to

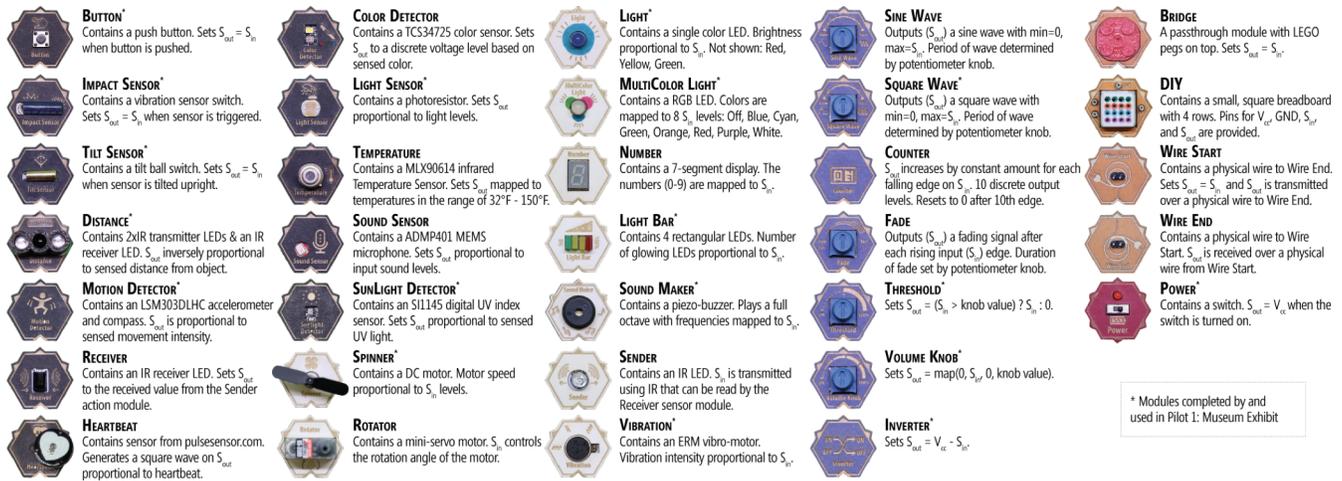


Figure 2. The final MakerWear prototype has 32 modules: 12 sensors (black), 9 actions (white), 7 modifiers (blue), 3 misc (orange), and 1 power (red).

leverage the richness of *wearability* and *mobility*—for example, changing environments, children’s bodies (*e.g.*, movement, physiology), and social interaction.

- **Augment daily experiences.** We aim to support designs that are personally meaningful and augment everyday experience, be it socio-dramatic play, soccer practice, or a dance recital.
- **Low floors, high ceilings, wide walls.** Extending from [47], children-oriented wearable toolkits should be approachable but also support the creation of sophisticated, multi-faceted designs as a child gains experience.
- **Tinkerable.** Because of a dual reliance on craft skills and programming, previous wearable toolkits limit children’s ability to *tinker* and *rapidly prototype*—two important aspects of the creative making process [46,57]. Wearable toolkits should allow children to easily try out multiple alternatives, to take things apart, and to create new versions.
- **Developmentally appropriate.** An overarching principle is to create developmentally appropriate designs informed by the literature and revised through iterative design.

THE MAKERWEAR SYSTEM

MakerWear is comprised of two parts: (i) single-function, ‘plug-and-play’ magnetic modules that can be combined to create complex interactive behaviors (Figure 2); (ii) a flexible, magnetic socket mesh that is either pre-integrated into clothing or attached *post-hoc* like a fabric patch (*e.g.*, via a safety pin or iron-on Velcro). The mesh provides power (V_{cc}) via an internal LiPoly battery, ground (GND), a communication wire ($Signal$), and an easy method to attach and remove modules. The modules and mesh are hexagonal, enabling creations to extend and branch into non-linear forms that are visually interesting and can adapt to clothing contours. Our architecture is scalable—allowing for large cascading designs—and responsive (*e.g.*, modules work instantly when placed and react within 10ms to input). The MakerWear system is open source, including hardware (schematics and board layout), microcontroller software, and design files: <https://github.com/MakerWear>.

Module design. Modules are 25.5mm across \times 9-30mm in height, depending on the embedded electronics. Each

module is colored by type with a laser-etched, child-friendly name and icon on the top layer. There are currently five module types: *power* (red), *actions* (white), *sensors* (black), *modifiers* (blue), and *misc* (orange). *Sensors* modules sense and translate physical phenomena into electronic signals (*e.g.*, light levels, heart rate, physical movement), *actions* translate signals into perceptual forms (*e.g.*, sound, light, vibration), and *modifiers* transform signals into other types of signals (*e.g.*, inverters, faders). *Misc* includes a *DIY* electronic module for building with raw electronic components and a wire module that allows users to jump across sockets or link multiple socket meshes together.

Each module contains a small embedded microcontroller (either an Atmel ATtiny85 or ATmega328), a custom printed circuit board (PCB), electronic components, and a neodymium magnet (Figure 3). The bottom of the module has small, spring-based conductive pins to robustly connect with the mesh. Most modules have one input signal side (S_{in}) and three output sides (S_{out}), indicated by triangular slots and tabs, which fit together like puzzle pieces. In our current prototype, S_{out} is shared (equivalent) on all three sides, but this is not intrinsic to our architecture and future modules could have multiple inputs and outputs. The two remaining sides remain open to prevent accidental connections in tightly packed configurations. While we experimented with

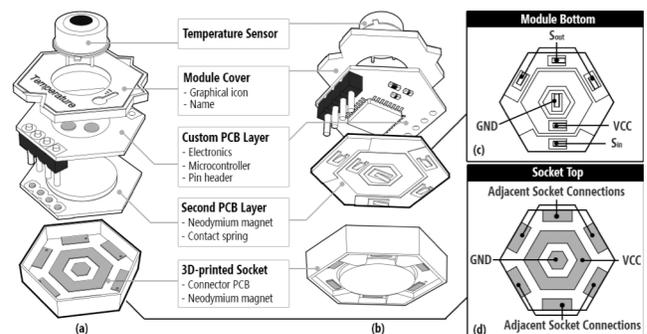


Figure 3. An exploded (a) top-down and (b) bottom-up view of an example MakerWear module and socket as well as overhead views of (c) module and (d) socket connector points. The contact springs ensure a robust connection.

both fabric and flexible PCB designs, current modules use a traditional rigid PCB with a laser-cut top made of matboard.

Module library. Selecting appropriate abstractions and providing a diverse catalog of modules is crucial to any construction kit. In addition to providing standard electronic modules (e.g., LEDs, vibro-motors), we focused on building modules that leveraged the unique opportunities of wearability, particularly: *body movement and physiology*, *social interaction*, and the *changing environment*. Modules range from low-level behavioral abstractions (e.g., an LED module) to higher-level abstractions (e.g., an accelerometer-based motion detector that outputs values corresponding to movement intensity). We have currently designed and built 32 modules (Figure 2). While a large number of modules can be overwhelming, the tradeoff is that too few modules could constrain creativity, especially as a user gains experience. As a comparison, Scratch Jr. has 25 programming blocks. In our studies, we introduce blocks incrementally, or exclude some more complicated ones altogether depending on age group.

Socket mesh design. The socket mesh serves two primary functions: (i) it provides power, GND, and a communication wire, and (ii) an easy, robust mechanism to attach/detach modules to clothes. Each hexagonal socket is made of a PCB base encased by 0.8mm 3D-printed walls. Similar to a wooden puzzle with precut slots, the sockets provide a strong visual affordance about how and where to place modules. We have created two types of socket meshes: those integrated directly into clothes (e.g., hats, scarves, vests) and a set of self-contained mesh patches that can be attached to clothes or other artifacts (such as backpacks) via safety pins or worn as jewelry. The meshes are individually wired and contain an integrated, rechargeable LiPoly battery. A small recharging cable is hidden in the fabric material. For the purposes of our research, we focused on clothing that could be easily taken on and off, such as hats, sleeves, and vests. Socket counts range from 14 sockets on a sleeve to 23 on a vest.

Creating with MakerWear. Wearable creations are built by placing correctly oriented modules in adjoining sockets on a mesh and adjusting on-module knobs, when available. All programs start with a *Power* module, which has six outputs, all of which set $S_{out} = V_{cc}$. The simplest functional program is thus *power* \rightarrow *action*. In this design, if the action module is a *Blue Light*, it would always be on. By adding a sensor, the design becomes interactive. For example, *Power* \rightarrow *Tilt Sensor* \rightarrow *Blue Light* would turn on the light when in the proper tilt position and *Power* \rightarrow *Light Sensor* \rightarrow *Inverter* \rightarrow *Blue Light* would turn on the light proportional to darkness level. Finally, because each module has three S_{out} connections, creating non-linear designs is straightforward. A single sensor module, for example, can be directly connected to up to three action modules, activating each simultaneously.

How does this work? All module behavior is contingent on its S_{in} , which itself is a function of all preceding modules in the input chain. Action modules forward their S_{in} to their S_{out} ($S_{out} = S_{in}$), while sensor and modifier outputs are a function

of two factors: for sensors, $S_{out} = f(S_{in}, \text{sensing value})$ and for modifiers, $S_{out} = f(S_{in}, [\text{on-module knob value}])$. We use a hybrid analog-digital design: the analog S_{in} is read in, digitized, and processed by a module's microcontroller and then converted back to analog for S_{out} using pulse width modulation with an RC low-pass filter for smoothing. To ensure that modules with different current consumption (e.g., *Spinner* vs. *Light*) would not cause brownouts, we isolate each module's S_{in} from the previous module by using an op-amp voltage follower or the microcontroller's ADC pin, which uses a high impedance input (100 M Ω)

Depending on the module, custom code on the microcontroller interfaces with its embedded electronics (e.g., via I2C) smooths out S_{in} using a small sliding window, and/or performs some signal processing. For example, *Counter* increases S_{out} by a set amount every time a falling edge on S_{in} is detected. *Actions* modules either map S_{in} into discrete actions (e.g., the *MultiColor Light* maps S_{in} into 8 different colors) or react proportionally to S_{in} 's voltage (e.g., the *Spinner* or *Vibration*). Similarly, sensors and modifiers either discretize their outputs—e.g., *Color Detector* has 8 and *Counter* has 10 voltage levels—or outputs an analog value between 0- V_{cc} . See Figure 2 for complete descriptions.

PILOT STUDIES

To gain preliminary understanding of *how* and *what* children could build with MakerWear and to uncover usability issues, we conducted two pilot studies: an interactive museum exhibit and a 1.5-hour workshop. Our findings were used to refine our final prototype as well as our workshop approach.

Pilot 1: Museum Exhibit

We hosted a 3-hour interactive MakerWear exhibit at a local children's museum. Though open to all attendees, the exhibit was in a small private room to ensure informed consent by a parent or guardian. We set up three MakerWear stations, two of which had a sleeve (14 sockets each) and one of which had a scarf (9 sockets). In total, 17 children participated (ages 4-16; 5 female) and spent an average of 20 minutes ($SD=13$ mins) using MakerWear. Unlike our later studies, no detailed demographic or questionnaire data was obtained. Two research assistants provided introductory demos to newcomers, answered questions, and facilitated making. At the time of this study, MakerWear had a total of 18 modules, which are marked with a * in Figure 2.

Results. Though time-limited and with minimal training, we observed an iterative process of playful experimentation, creation, and testing. Children made a wide range of designs from a simple, button-activated, light-up scarf to a go-away, sneak-up alarm system. Some children reappropriated lo-fi materials from the museum into their designs. Common challenges included: difficulty comprehending module behaviors (especially modifiers), sequencing issues (placing actions *before* sensors), and some small technical issues (e.g., faulty socket wiring). Younger children tended to create simpler designs, often only using action modules, and had a tendency to fill up every available socket; however,

they also seemed to enjoy themselves. For example, a mother commented about her 4-year old son: “*he hasn’t been captivated like that for any other activity in this museum.*”

Outcomes. Informed by this experience, we made a few key improvements: (i) we provided more explicit support for lo-fi integration by adding LEGO pegs and Velcro to the *Rotator* and *Bridge* and brought lo-fi materials to our sessions; (ii) we increased the number of sockets on MakerWear clothes and introduced a wire module to connect multiple meshes; (iii) we created 12 additional modules to inspire a greater diversity in designs, including the *Rotator*, *Number*, *Heartbeat*, *Temperature*, and *Sender* and *Receiver*. These revisions were made before our next pilot evaluation.

Pilot 2: Single-Session Workshop

To help test the revised MakerWear platform and trial our workshop plan, we conducted a 1.5-hour pilot with 6 children (4 female) ages 5-9 ($M=6.8$; $SD=1.3$). At this point, we had 30 modules (everything except *Sound Sensor* and *Bridge*); however, only 20 were used here due to time constraints. Participants could choose from nine pieces of clothing: two vests (23 sockets), two sleeves (14), two hats (15 and 19), one scarf (19), and two fabric patches (19). The session began with a questionnaire and a demonstration then alternated between introducing new modules and playtime.

Results. While more structured than the museum exhibit, our results were, surprisingly, more mixed. Though five of the six participants were able to build basic designs using power and action modules as well as a simple modifier, the *Volume Knob*, only a few were able to confidently build more sophisticated designs (e.g., with sensors). Moreover, sequencing continued to be a challenge, especially for younger participants. Despite these issues, we observed children making connections to their everyday life, being able to accurately describe their designs, and using modules to help problem solve. For example, Zara (girl, age 7) made *Power* → *Impact Sensor* → *Light* and said, “*This is exactly how light-up shoes work. When you stomp your shoe, it would light up.*” Later, she used a *Light Bar* to visualize the signal between a *Volume Knob* and *Sound Maker* and stated “*I made something to show how much power is going up.*”

Outcomes. We identified three key areas of improvement: (i) we appeared to overwhelm the children with content and new modules, which caused confusion and frustration; (ii), unsurprisingly, we found that the two younger children needed more time to play with and understand each module; (iii) finally, some of the new sockets and modules malfunctioned, further inducing frustration and confusion. To address these issues, we rewrote our workshop plans to reduce content, split the workshops into age groups, and implemented a more comprehensive testing procedure to find and fix errors before our deployments.

STUDY 1: SINGLE-SESSION WORKSHOPS

With a refined MakerWear platform and workshop protocol, we ran two single-session workshops at a local children’s museum ($N=13$; ages 5-12). The goals were similar to our

pilot studies—to examine the approachability of MakerWear and *how* and *what* children make. A secondary goal was to help inform the design of our multi-session workshops.

Method

Participants were recruited via the children’s museum. Sign-ups occurred online with one session for ages 5-7 and one for ages 8+. The workshop was free apart from museum admission (\$12). We had five participants (all female) in the younger session and eight (3 female) in the old. See Table 1. Four parents also attended (3 in younger, 1 in older) who provided constructive prompts, helped facilitate making, and offered emotional security, especially to younger children.

N	Age	Gender	Computer Use	Graphical Prgmng Exp.	Electronics Experience
5	$M=6$ <i>Range=5-7</i> $SD=1$	5 girls	1 Multiple times a day 4 A few times a week	1 A few times a week 1 A few times a month 3 Never	1 A few times a month
8	$M=9.9$ <i>Range=8-12</i> $SD=1.5$	3 girls 5 boys	6 Multiple times a day 1 A few times a week 1 Never	1 Once a day 2 A few times a month 5 Almost never/never	2 A few times a week 2 A few times a month 4 Almost never/never

Table 1. Single-session workshop group sizes and demographics.

Procedure. Sessions lasted just over 1.5 hours and included: a pre-study questionnaire (10 mins), an introduction to MakerWear (5 mins), building/playing with MakerWear (70 mins), and a post-study questionnaire (10 mins). A team of three researchers facilitated each workshop. Based on our pilot studies, we prepared slightly different workshop plans for the two age groups (Figure 4). The older group had a faster pace, which allowed us to introduce additional modules and design challenges. To reduce confusion and provide time for playful exploration, we used only a subset of our module library—10 modules for the younger group and 16 for the older group (Table 2). New concepts and modules were introduced incrementally, starting with *Power* then simple actions. When a module was first introduced, we would either explain and quickly demo the module or ask the children to experiment and figure it out themselves. Children had ~5 minutes of playtime to explore each new module. We used the same clothing as in Pilot 2 but with two new larger sleeves (20 sockets each). Participants selected their clothing at the beginning of the workshop but could switch anytime.

To help assess understanding as well as computational and problem-solving skills, we conducted two design challenges in the ages 5-7 workshop (*Wearable Instrument* and *Dance Freeze*) and three in the 8+ workshop (*Auto-Flashlight Clothes*, *Buzz Lightyear*, and *Dance Freeze*)—see Figure 5. The workshop ended with a “*Dance Freeze Game*” where children danced wearing their *Dance Freeze* designs- in a game similar to musical chairs. When the music stopped, the children had to stop dancing. They were eliminated if their designs were still flashing lights and making sounds, which

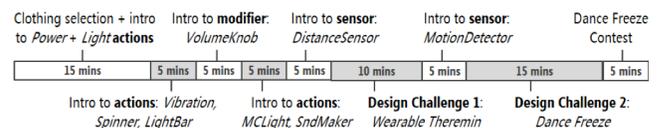


Figure 4. The single-session workshop plan for ages 5-7. After receiving a new module, children had ~5 minutes of playtime and experimentation. The workshop for 8+ was similar but had 16 modules and 3 design challenges.

indicated that they were still moving. During the session, researchers intermittently performed artifact-based interviews [9] to assess understanding and design motivation. Three long mirrors allowed children to see their creations while wearing them.

Ages	Actions	Sensors	Modifiers	Total
5-7	Light, Vibration, Spinner, Light Bar, MultiColor Light, Sound Maker	Distance Sensor, Motion Detector	Volume Knob	10
8+	+Rotator	+Light Sensor, +Tilt Sensor, +Impact Sensor, +Button	+Inverter	16

Table 2. Modules used in our single-session workshops.

Data and Analysis

We used a mixed-methods approach to assess understanding, computational thinking, subjective factors (*e.g.*, enjoyment), as well as to analyze how children made with MakerWear, what they made, and challenges therein. We analyzed session video, design challenge performance, artifact-based interviews, and the pre- and post-study questionnaires. The pre-questionnaire collected demographic data and prior relevant experience. The post-questionnaire asked about how participants felt about MakerWear and their designs as well as questions assessing understanding of module behavior, sequencing, and other computational thinking principles. Questionnaires used a mixture of closed-form, age-appropriate Likert-scale questions [19] as well as free response. For some younger children, questions were individually read by a researcher and responses transcribed.

Multiple video cameras captured how children used MakerWear and their facial expressions, physical movement, and social interactions. To analyze session video, we used a thematic coding approach with a mixture of inductive and deductive codes [8]. Two researchers created an initial codebook based on study goals and pilot study experiences, including for *engagement, use of modules, troubleshooting behavior*. One researcher coded sample video from the 8+ group, concurrently updating the codebook to support new themes. Two researchers then coded the remaining videos, discussed their findings, and co-interpreted the data.

Findings

We describe key themes and common patterns related to making with MakerWear. For the Likert-scale questions, we report means (*M*) and standard deviations (*SD*)—a score of 5 is best. All names are pseudonyms with (age, gender).

Making with MakerWear. Children across both age groups were engaged in making throughout the workshop. Because of the workshop structure and pace, children did not have time to create their own designs like we observed in the museum exhibit or later in the multi-session workshops. Instead, their focus was on understanding and building with modules and completing the design challenges. In terms of MakerWear clothing: six used sleeves, four used the fabric patches, two used hats, and one used a scarf. Interestingly, rather than affixing the fabric patch to clothes, a child in the younger group adapted it with string to wear it as a necklace.

Two styles of making emerged, which was at least partially influenced by clothing type: seven children spent most of

their time iteratively building and testing their designs while *wearing* their clothing (6 sleeves, 1 vest). The other six children primarily built on a table and then infrequently switched to wearing for testing. Of course, some clothing like the two hats made it difficult to build a design while wearing it. Across both groups, children took advantage of the three module outputs and made branching, non-linear designs with interesting visual patterns. While designs with multiple actions were common or even sequences such as *action* → *sensor* → *action*, very few children cascaded two sensors together. One exception was: Dmitry (12, boy) who combined a *Button* and a *Tilt Sensor* so that a button press would only work when his design was tilted.

To troubleshoot, children employed three common strategies: (i) they removed and re-added a module either to the same socket or to a neighboring socket that created a functionally equivalent design; (ii) they re-ordered modules around until their design worked as expected—this was the most common solution to solving sequencing issues; and/or (iii) they asked a researcher, parent, or another child for help.

Understanding MakerWear. We analyzed how children understood MakerWear-specific concepts (*e.g.*, actions *vs.* sensors, individual modules) as well as higher-level principles related to computational thinking: sequencing, branching, and logic. When first introduced to MakerWear, children quickly understood basic concepts: a *Power* module is always needed to start a design and that modules had to be in neighboring sockets to be connected. Some children struggled initially with orienting inputs and outputs, which was corrected by facilitators using a puzzle analogy and focusing attention on the I/O triangles. All 13 participants struggled initially with sequencing (*e.g.*, modifiers and sensors must come before actions), particularly in the younger group. This was mostly resolved by the session’s end, as evidenced by their design challenge performance and post-study questionnaire responses. For example, on the questionnaire, 12 children (92.3%) correctly fixed a design that had an ordering problem. The one participant who got it wrong (Sayuri, 5, girl) left it blank.

On the post-study questionnaire, all children correctly described action modules—*e.g.*, “*they do something like light or move*” (Brody, 8, boy). In contrast, for the *Volume Knob*, which is a modifier module and therefore potentially more complicated, all of the older children described it properly —*e.g.*, “*it allows you to control how much power gets through to power the other modules*” (Brian, 12, boy) but only two younger children did: “*it controls volume and controls actions*” (Angel, 6, girl). For those who got this wrong, we observed proper use in our video analysis (*e.g.*, to change light color, sound), so the problem may have been in articulating this knowledge on a written questionnaire. Children also exhibited understanding through their artifact-based interviews. For example, when asked to describe her design, which contained three branches, Angel (6, girl) stated “*the power comes from here [points at the Power module] and then it kinda travels here, here and also travels here.*”



Figure 5. The design challenge descriptions and example solutions used in the single-session workshops.

In summary, children seemed to understand differences between module types, module behaviors, and higher-level principles like sequencing and how a signal traverses through a design; however, they had little exposure to modifiers, multiple sensors, and few opportunities to demonstrate understanding of more complex concepts like conditionals.

Design challenges. Generally, most children were able to complete the design challenges (Figure 5). For the younger group, all five children successfully created their wearable instruments; however, Elise’s (5, girl) father helped her determine which modules to use though she placed them correctly herself. For the older group, all eight children were able to make their auto-flashlight clothes; however, one child required some prompting (e.g., “remember which module allows your design to do the opposite thing”). For the two harder challenges, *Buzz Lightyear* (only for older group) and *Dance Freeze* (both groups), performance was more mixed but still largely positive. For *Buzz Lightyear* (Figure 5c), seven children built the tilt-based rotating shield but only five were able to create a design that correctly alternated between attack and shield mode. While we used this challenge to examine understanding of the inverter and control structures, two children created unexpected designs that, instead, used two parallel ‘threads’ extending from *Power*. For example, Ellie (9, girl) created two independent branches: (*Power* → *Tilt* → *Rotator*) and (*Power* → *Button* → *Light*); however, this is only partially correct because both the shield and attack modes could be activated at the same time.

Finally, for the *Dance Freeze* challenge (Figure 5d), seven children (1 from younger; 6 from older) confidently built and tested a successful design with no assistance. Three children in the younger group and all children in the older group were eventually able to create working designs with minimal prompting (e.g., “remember, your design should also make sound when you are dancing”). Two younger children received significant assistance from their parents, so we did not count these in our assessment. Children enjoyed playing the *Dance Freeze Game* with their designs, particularly the older children who asked to play three full rounds.

Overall reactions. In their post-study questionnaires, all 13 children reported wanting to use *MakerWear* again ($M=4.8$; $SD=0.4$) and to bring their design home ($M=4.9$; $SD=0.3$). All but one child reported having fun ($M=4.4$; $SD=0.9$). The exception was Leiko (7, girl) who marked a ‘2’, but in video analysis was engaged and smiling, and quickly and successfully completed her design challenges. Finally, all but one child reported being proud of their creations ($M=4.3$; $SD=1.1$). The exception was Angel (6, girl) who selected 5’s

on all other Likert questions. When asked to select a favorite module, action modules were selected most frequently, including the *Sound Maker* ($N=5$ votes) because ‘you can change the sound’ (Hiroka, 7, girl), the *MultiColor Light* ($N=3$) because ‘it changes color’ (Ellie, 9, girl), and the *Distance Sensor* ($N=2$) because ‘it’s like magic’ (Jay, 9, boy). When asked to describe the coolest thing about the workshop, 10 of the 13 children mentioned something that they made such as *Buzz Lightyear* or *Dance Freeze*.

Summary. In summary, our findings show that children across age groups were able to understand basic principles such as power, I/O orientation, and sequencing and apply these to build with *MakerWear*. However, the workshops were time-constrained and focused primarily on basic modules (with the exception of the *Inverter* in the 8+ group).

STUDY 2: MULTI-SESSION WORKSHOPS

To gain deeper insight into how children use and understand *MakerWear* over longer periods of time with a wider variety of modules, we conducted three four-day workshops in after-school programs at two local community centers.

Method

Participants were recruited through the after-school programs and informed consent was obtained before the first workshop. We had 19 participants in total, who were split into different sessions by age: youngest ($M=6.3$ years), middle ($M=8.8$), and oldest ($M=10.2$)—see Table 3.

Procedure. Sessions lasted ~1.5 hours and roughly followed the single-session format, intermixing the introduction of new modules with design challenges; however, the multi-sessions covered more content, allowed for more open playtime, and, following Bers *et al.*’s *TangibleK* robotics curriculum [6,55], included a final design project (Days 3 and 4). Children completed a pre-study questionnaire at the beginning of the first day. All subsequent sessions started with two ‘fix-it’ design challenges where children were given pre-made designs with a problem and told to fix it. Each day ended with a ~10-minute post-study questionnaire.

The final project design process was open-ended. Children brainstormed, sketched, and implemented their ideas with intermittent feedback from peers and workshop facilitators. Lo-fi materials like fabric, pipe cleaners, ping pong balls, and LEGOs were provided. On Day 4, projects were presented to family members and peers at an informal exhibition. Overall, we introduced 21 modules in the youngest group—most of the actions and sensors but only two modifiers (*Volume Knob* and *Inverter*)—and 31 in the middle and oldest groups (no *DIY* module because covering circuits was beyond the workshop scope). At least two researchers and one program



Figure 6. A subset of final projects, including: (a) Omar’s wrecking-ball superhero armband, (b) Sarah’s sneak attack lacrosse alarm system, (c) Kevin’s sound-reactive armband, (d) Amelia’s jogging clothes, (e) Jake’s fitness tracker, and (f-g) Austin’s wireless Pokémon. See supplementary video.

staff helped facilitate sessions. We used the same mixed-methods approach as Study 1 to analyze Study 2 data.

Findings

We present findings uniquely afforded by the multi-day evaluation: (i) what children designed and built for themselves with their final projects; (ii) age-related differences; and (iii) how children progressed in their understanding and use of MakerWear.

Final projects. Unlike the built artifacts from the single-session workshops, the final projects (Figure 6) allow us to understand what children *can* and *choose* to create after gaining experience with MakerWear. For analysis, we focused on project themes, how children used modules in their designs, and the complexity of the artifacts themselves (e.g., number of modifiers). The most common theme was sports/fitness (6 designs), followed by role-play characters like superheroes (5), socio-dramatic play (2), and decoration (2). Two children brought materials from home to use in their designs: a lacrosse stick and a Pokémon doll. In terms of sensing, children most commonly sensed: movement (7 designs), physical actions like pressing or twisting (5), the environment (4), physiology (3), or social interactions (2). Seven designs used at least one modifier, four used more complex control structures with *Inverters* and *Thresholds*, and all but one design integrated lo-fi materials.

For the designs themselves, the sports projects included both equipment and clothing augmentation. For example, Sarah (9, girl) added a *Distance Sensor* to her lacrosse stick along with *MultiColor Lights* and a *Sound Maker* to warn her when someone was about to take the ball. Amelia (10, girl) created intricate jogging clothes that included four meshes: a left sleeve that tracked and beeped on every heart beat by using a *Heartbeat Detector*, a *Counter*, a *Number* display, and a *Sound Maker*, a right sleeve with two *Spinner* fans controlled by a *Volume Knob* to cool her down, and a safety vest and hat that lit up in the dark using a *Light Sensor* and *Inverter*. Finally, Jake (11, boy) made a fitness tracker to count steps and, using a *Threshold*, reward the wearer with flashing lights and sounds if they reached 900 steps.

N	Age	Gender	Computer Use	Graphical Prgmng Exp.	Electronics Experience
7	M=6.3 Range=5-7 SD=0.8	3 girls 4 boys	6 At least once per day 1 A few times a week	4 Indicated some exp. 3 Never	4 Indicated some exp. 3 Never
6	M=8.8 Range=8-9 SD=0.4	1 girl 5 boys	4 At least once per day 1 A few times a month 1 A few times a month	1 A few times a week 2 A few times a month 3 Almost never/never	2 A few times a week 2 A few times a month 2 Almost never/never
6	M=10.2 Range=8-12 SD=1.3	4 girls 2 boys	3 At least once per day 2 A few times a week 1 A few times a month	3 A few times a week 2 A few times a month 1 Almost never	3 A few times a week 1 A few times a month 2 Almost never/never

Table 3. Multi-session workshop group sizes and demographics.

Role-play characters were more fantastical. For example, Omar (6, boy) made a wrecking-ball superhero armband that lit-up, made sound, and moved a ping-pong ball and pipe cleaners via a *Rotator* when a button was pressed, while Dan (7, boy) made a ninja armband that vibrated and flashed lights when he performed an uppercut. Finally, as an example of socio-dramatic play, Sean (10, boy) made a *Harry Potter Sorting Hat* that could tell if someone belonged to Gryffindor or Slytherin. This hat had a social element: one child held the hat while another wore a scarf. The scarf detected what color the person wore (an “evil” or “good” color) and transmitted the data to the hat, which in turn lit up to indicate Slytherin or Gryffindor. These examples illustrate the range of creative possibilities that MakerWear was able to support. See our supplementary video.

Age-related differences. We analyzed differences related to how children built with MakerWear, the modules they used, the sophistication of their projects, and their understanding of key principles. A quantitative analysis of final projects is shown in Table 4. Unsurprisingly, as age increases, children used not only more modules in their final projects but also more complex modules like modifiers with sophisticated structures (e.g., using *Inverters* or *Thresholds*). Interestingly, the opposite appears true with integrating lo-fi materials—the two younger groups, on average, used about two pieces of lo-fi material each while the older group used less than one piece. In the most extreme case, one child (Kayla, girl, 6) made her final project, a puppet, entirely out of lo-fi materials without any modules. Younger children were also more likely to use simple sensors like *Buttons* to create interaction compared with older children.

Using fix-it challenge and questionnaire data, we analyzed sequencing, branching, and complex cascading (e.g., *sensor* → *sensor* or *modifier* → *sensor*). We had four fix-it ‘sequencing’ challenges on Days 2 and 4. The youngest group successfully solved 81% of the challenges while the two older groups solved 100%. Interestingly, while we asked similar questions on end-of-day questionnaires—e.g., by showing a picture of a design with an ordering problem—all children performed worse here: the youngest group scored 44% and the middle and oldest groups ~90%. For branching, we showed two

Group	# Modules	# Sensors	# Modifiers	# Ctrl Strctrs	# Branches	# Lo-Fi
5-7	5.8 (3.7)	0.8 (0.4)	0 (0)	0 (0)	0.6 (0.9)	2.0 (1.3)
8-9	9.3 (4.7)	1.2 (0.8)	1.0 (0.5)	0.5 (1.2)	1.3 (1.0)	2.3 (2.1)
8-12	18.1 (14.2)	2.7 (1.5)	3.7 (1.5)	1.0 (0)	2.0 (3.1)	0.7 (1.2)

Table 4. A quantitative analysis of final projects with format. Cells show average/design and SD. *Ctrl Strctrs*=Control structures refers to designs that used thresholds or inverters to setup conditionals. *Branches* refers to the number of times more than one output of a module was used.

functionally equivalent designs on Day 4, one using linear branching and one using non-linear branching. All of the older children correctly stated that the two designs do *not* behave differently but only two (33%) in the youngest group did. Finally, we observed only one child in the youngest group use complex cascading—LeShawn (7, boy) who used *Tilt Sensor* → *Inverter* to complete a design challenge; these structures were far more common in the two older groups.

In summary, all children were able to create designs with MakerWear and generally understood basic concepts (*i.e.*, I/O orientation, sequencing). The younger children, however, created simpler designs, had difficulty with more complex concepts, and a few struggled even on Day 4 with some basic-to-intermediate principles like branching.

Progressions. We also examined how children’s use and understanding of MakerWear changed over the four days as they acquired more experience and more modules were available. Children demonstrated learning both through how they made designs and their questionnaire responses. For example, on Day 1 only 47% of children answered sequencing questions correctly; this jumped to 77% on Day 4. Keisha (6, girl) said, “*I remembered that if you put the lights with power, it’s just gonna stay on but if you put it after the distance, it will change.*” For the *Threshold* module, which was only used in the older group, 20% of children correctly answered questions on Day 3, rising to 78% on Day 4. Two children used a *Threshold* in their final projects. Finally, introducing new modules opened new opportunities for learning and design. For example, children used the *Wire* module not just to skip sockets, as expected, but also to connect across meshes and to spread out their designs (*e.g.*, to isolate an *Impact Sensor* from reacting to *Vibration*).

Overall reactions. When asked what they thought of MakerWear on the end-of-study questionnaire, all but two participants selected ‘5’ ($M=4.9$; $SD=0.4$). When asked to describe their favorite activity, the most common response was the final project ($N=7$): “*My lacrosse stick, because it represented me and what I like to do*” (Sarah, 9, girl), “*my own super hero thing*” (Mike, 9, boy), and “*my final project because it was hard to use and fun to make*” (Keisha, 6, girl).

DISCUSSION AND CONCLUSION

This paper contributes a new tangible, modular approach to wearable design called MakerWear. Our findings show that children across our target range (K-6) were able to successfully create a wide variety of wearable designs, actively apply computational thinking (*e.g.*, I/O, sequencing, logics), and create artifacts of which they were proud. In the multi-session workshops, children designed and built final projects that both leveraged the unique properties of wearability and augmented meaningful experiences and objects in their lives (*e.g.*, sports, fictional characters).

Design tradeoffs. While the MakerWear platform lowers barriers to wearable design compared to previous kits, there are tradeoffs. First, the role of craft and aesthetics—which is not just a key part of fashion but also touted as one reason

why previous wearable toolkits have been successful in broadening participation in CS [26,28,50]—is deemphasized in MakerWear. Future work should explore how to better integrate craft opportunities, perhaps by involving children in socket creation and/or by providing more modules, like the *Rotator*, that easily interface with craft materials. Second, while the textile-integrated socket mesh enables our tangible, plug-and-play approach, the mesh itself is not fabric, is relatively heavy, and requires expertise to build. The socket mesh patch (visible in Figure 6f) may offer a nice compromise; it provides the benefits of tangible wearable design but can be attached to any material. A flexible kit should provide the option of specialized clothing or patches to allow for retrofitting of existing clothes.

Third, the sole reliance on a tangible, modular approach limits designs to available modules in contrast to completely open kits (*e.g.*, [41]). To address this concern, we are currently exploring a hybrid tangible-graphical approach [20] that will allow older children or more experienced users to program modules via a touchscreen interface. Moreover, the *DIY* module, which we did not evaluate in this paper, provides another opportunity for more open-ended projects by allowing children to create their own modules from raw electronic components. Modules like *DIY* may serve as introductory pathways to more complex kits like LilyPad.

Robustness and power. At this stage in our research, we focused on usability, engagement, and enabling creative design rather than addressing pragmatic wearable concerns such as weight, robustness, and power. While our STEM educators raised concerns about the robustness of an early MakerWear prototype, we did not see a single module fall off during evaluations; however, a few modules did break with use (primarily magnets becoming detached). In terms of power analysis, individual modules draw between 9-96mA ($M=24.8mA$) for sensors to 5-80mA ($M=46.5mA$) for actions. A 14-socket mesh completely filled with the highest current-drawing action modules in their fully-on states draws ~644mA, while a more average design draws half that. Most children’s creations, however, include interactivity so are not always fully on, reducing power consumption.

Study limitations. We evaluated MakerWear using a workshop-based study methodology that, while common for construction kit research [11,23,29,34], makes it difficult to assess the effect of curriculum and adult facilitation on outcomes. More research is needed to examine how children would use MakerWear in less-structured environments and for longer periods. Moreover, while we provided both a qualitative and quantitative assessment of age-related differences in using MakerWear, the latter was limited by the content and modules introduced in each workshop, which was imbalanced (the youngest group used 20 modules, the two older groups 30). We have recently partnered with two organizations to examine more longitudinal uses of MakerWear—specifically, in the context of children creating wearables for sports programs and community theatre.

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