Design and Evaluation of DIO Construction Toolkit for Co-making Shared Constructions

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Fig. 1. Children engaging with constructions formed by connecting DIO input modules (red) with output modules (blue)

We present the design and implementation of *DIO*, a novel digital-physical construction toolkit to enable constructionist learning for children from age group 8-12 years. The toolkit comprises of dome-shaped (**D**) tangible modules with various attachments that allow suspension on the body of multiple children and/or in the environment to support a variety of sensing/input (**I**), actuation/output (**O**) functionalities. The modules are enabled for wireless communication and can be linked together using an Augmented Reality based programming interface running on a smartphone. The smartphone recognizes our hemispherical modules omnidirectionally through novel computer vision based 3D patterns; custom made to provide logical as well as semantic encoding. In this paper, we show how, owing to its unique form-factor, the toolkit enables multi-user constructions for the children and offers a shared learning experience. We further reflect on our learning from a one-year long iterative design process and contribute a social scaffolding based procedure to engage children with such constructionist toolkits effectively.

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CCS Concepts: • **Human-centered computing → Interactive systems and tools**; *Collaborative interaction*; *Interaction design process and methods*.

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1 INTRODUCTION

For a long time now, educational researchers have emphasized the importance of computational thinking in STEM education for young children [10]. Such thinking enables children to use concepts from computer science to solve problems, and understand their worlds in better ways [59]. This has lead to the development of computational toolkits aimed at developing such thinking among the children [61]. In today's digitally mediated society we are surrounded by *internet-of-things (IOT)* based devices that assist us in our everyday lives. Hence, there is a growing need of introducing children to the affordances of these new technologies such that they don't just use them but are fluent in developing new designs using them [51]. Addressing this requirement, we developed a new toolkit *DIO*, based on a *distributed design* form-factor, inspired from IOT technologies. *DIO* comprises of input, output modules that communicate wirelessly, and can be connected using an augmented reality based interface to implement a variety of interactive applications. The modules can be suspended on to bodies of multiple children as wearables or into the environment like on a wall.

Digital-physical construction toolkits comprise of electronic building blocks hosting a variety of sensing, actuation capabilities; that can be combined together to create a variety of constructions. Their working can be described on the basis of the theory of constructionism given by Seymour Papert, who established how children learn in designing and creating things that are meaningful to them [39]. Since then researchers have developed a variety of toolkit designs, as surveyed by Kelleher et al. [31]. While engaging with these construction toolkits, children develop an understanding of the associated concepts that the toolkit operates on (*powerful ideas* [40],) like physical stability in LEGO, looping and data structures in programming kits, etc. This toolkit-based approach towards learning has been observed to be very effective in the past [7], and through DIO, we apply it towards learning about the internet-of-things. In the paper, we show how, creating interactive applications with DIO helps children understand concepts related to IOT technologies like input-output pairing, wireless communication, in addition to sensing, actuation functionalities of different modules.

Toolkits based on tangible manipulatives have been successful in teaching programming fundamentals to children [21]. Recently, toolkits based on wearable form-factor have been used to create designs that are "potentially always available" with the child, and hence can easily become a part of his/her everyday experiences [9, 30, 38]. In *DIO*, this design expands the advantages of wearability to multiple children, who can all wear the modules on their bodies. *DIO* modules worn by children on their bodies fall into their respective *personal space*, while the modules attached on to the environment fall in a common *social space*. This arrangement allows the children to work as design partners and engage in collaborative learning. Research has demonstrated that collaborative learning can enable higher achievement and productivity, foster supportive relationships, and social competence among children. Baranauskas et al. have showed how collaboration can further strengthen the goals of the theory of constructionism [3]. In spite of such benefits, not many construction toolkits have defined collaboration as a design goal. We show how the *DIO* toolkit fills in this gap by enabling shared making, learning experiences for the children.

To build the *DIO* system, we followed an iterative design process spanning across a duration of a year. We started with a workshop design session with the children in which we used low-fidelity material to check as to what they would make around the ideas of body, environment-mounted input and output modules. This was followed by iteratively building and pilot testing prototypes with our target users. Informed by these insights, we build our final system that enables children to create multi-user constructions, and to learn in the process. We report on our findings related to different research goals and reflect on the general trends of collaboration that we observed. We defined 6 research goals based on prior work in designing construction toolkits. They are as follows.

(R.G. 1) **Usability of the toolkit:** Our most basic research goal was to gauge whether the children were able to use the system. This can include being able to identify the modules, using the augmented-reality based programming application to connect the modules, and to develop general understanding of the system, including the purpose of different input, output modules.

(R.G. 2) **Problem-solving using *DIO*:** Problem-solving is common in programming activities, and hence a significant characteristic of systems that enable programming as explored in previous work on construction toolkits [60]. We supported this research goal by testing how easy or difficult it is for children to implement a target application using the toolkit.

(R.G. 3) **What do the children make?:** Through the *DIO* system, we introduced the children to the novel form-factor of shared input, output modules that could be worn on their bodies or could be mounted in their environment. Hence, we noted what do the participants create given these new possibilities.

(R.G. 4) **Development of understanding regarding the associated concepts:** We hypothesized that by working with the *DIO* toolkit, the children would become fluent with the functionalities of the technologies around them and would understand their environments better. To check regarding this hypothesis, we presented the participants with questions to gauge if they were able to apply the learnt concepts in scenarios from their everyday lives.

(R.G. 5) **Subjective factors:** This goal includes probing the children's views on the *DIO* toolkit. Whether they like it, do they find it easy to use, or their general experience of engaging in the co-making activity.

(R.G. 6) **Trends of collaboration:** Our system is rooted in co-making and multi-user experience. Thus, we expected the children to work as partners, in collaboratively making the constructions. Moreover, we wanted to validate the usage of personal and shared spaces during construction activities. Hence, we reflect on the collaboration themes that we observed.

In summary, our contributions are as follows:

(1) The design and implementation of the *DIO* toolkit including the modules, and the augmented reality based interface for programming.
(2) Findings from the pilot study, evaluative user studies in context of the 6 research goals (R.G. 1-6) mentioned above.
(3) Finally, we reflect on our learnings from engaging children in constructionism-based making activity using our toolkit, which can be applied to other future toolkit designs.

2 RELATED WORK

Our work is related to design of construction toolkits. We borrow from perspectives from scaffolding techniques in education, and from the research on shared learning experiences.

2.1 Computational Kits and Programming Tools

Researchers have designed and developed a variety of computational kits and toys aimed at developing computational thinking among the children [59]. By letting children to program, these kits help them understand a variety of computational concepts (sequences, looping, parallel operation,) and computational practices (being iterative, debugging, etc.) [60]. In their recent survey, Yu and Roque have provided a summary of this space [61].

The programming interface is usually based on the *block as a puzzle piece* paradigm, wherein the blocks representing different programming structures/ commands that can be arranged by the children to design different programming behaviour [61]. Such interface is manifested in form of a Graphical user interface (controlled through a mouse) [8, 34] or as a tangible platform [19, 25]. Tangible platforms comprising of physical programming blocks are especially preferred for younger children owing to their ease of use [22]. However, Horn et al. have suggested hybrid interfaces (comprising of tangible and GUI-based parts) as a better alternative [20]. They have argued that such interfaces let the teacher and the students switch between tangible and GUI-based programming in different situations, and hence offer a great amount of flexibility.

Our toolkit comprises of physical blocks that can be attached in the environment or on the bodies of multiple children. The blocks are programmed through an Augmented Reality (AR) based interface, after which they communicate wirelessly to implement various designs. AR has recently gained popularity in supporting learning-based activities related to sentence formation [12], astronomy [13] and environmental awareness [42]. In addition to affording the dynamism, flexibility of hybrid interfaces, AR has been observed to provide effective feedback, reduce cognitive load, and enhance the enjoyment associated with learning [45]. In case of *DIO*, AR serves as an effective programming method supporting the distributed design of the toolkit. This approach is partially inspired from *Reality Editor*, an AR-based tool to design interfaces around programmable physical objects [17]. DIO is the first effort in utilizing such programming technique in developing construction toolkits for learning. We show how this novel approach leads to enhanced learning of associated concepts, and effective making activity using the toolkit.

2.2 Constructionist Toolkits

Construction toolkits aim to teach programming concepts, computational thinking by letting children construct things. Typically, these toolkits constitute of simple parts that the children associate together through programming and hence create a variety of constructions. Such toolkits are based on the theory of Constructionism given by Seymour Papert which stated that best learning experiences happen when the learner is actively involved in designing and creating things; things that are meaningful to them, are share-able with other people [39]. Blikstein [7] and Kelleher et al. [31] have provided comprehensive surveys of such construction toolkits.

Such toolkits allow their users to make a variety of things like virtual stories [44], programmable robots [46], and personalized wearable devices [9]. Comprehensive framework provided by Resnick and Silverman has been used to evaluate the *expressivity* of these designs [43]. Specifically *wide walls* and *high ceiling* indicate the diversity and complexity of constructions that can be designed using any toolkit. Popular among different construction toolkits are the electronics-based toolkits that enable constructions around *physical computing* [4, 15, 48]. Typically, these toolkits consist of input (for sensing), output (for actuation) devices that can be combined to create a variety of applications. Such toolkits enable children to bring their programs to the physical world that they live in, hence allowing them to understand how the world works. This relates to the idea of *technological fluency* defined by Papert which states how the children should not just use the technology around them, but should also be *fluent* in making things using it [40]. Our toolkit consisting of input, output modules that are attach-able into the environment or onto bodies of the users can be used to create a great variety of interactive environments. Children construct much of their knowledge through active manipulation of the environment [5]. Hence, poking and playing with the interactive constructions created using *DIO* modules can enable children to learn a great deal about their immediate environments that are replete with smart sensing and actuation devices. Moreover, the wireless communication based transmission of data resembles the design of the *internet-of-things (IOT)* systems that encumber our lives.

Papert had stressed that the engagement of children is heightened when the constructions are of personal interest (i.e. *personally meaningful*.) This focus has recently led research on constructionist toolkits having a wearable form-factor [30, 38]. Wearables being close to our body become part of our identity facilitating personalization and expression, and hence are meaningful to the individual. *DIO* expands this aspect of wearability to multiple children who can all wear their designs and can interact with one another. This along with environment based constructions allow group ownership and shared interests, hence facilitating collaboration. Moreover, unlike the existing wearable toolkits wherein the modules can be attached onto a specific body part, the *DIO* modules can be individually attached onto the different body locations, hence increasing the design possibilities (wider walls). Distributed design is a significant design feature of the *DIO* toolkit that enables these affordances.

Constructionist toolkits utilizing a distributed design have been scarce. *BlockyTalky* [50] is computer music toolkit comprising of distributed networks of sensors and synthesizers. Through this design, the researchers enabled multiple children to simultaneously manipulate the output composition, and make music in a collaborative manner. Their implementation however used LEGO Mindstorms sensors and Raspberry Pi network hubs that made the system bulky and predominately wired, limiting its use especially for younger children. The availability of low-cost, compact BLE hardware has motivated some new designs recently. *Unruly Splats* [1] and *Scratch Nodes* [18] are two work-in-progress projects that aim to utilize distributed designs to enable play-based learning. Essentially, the distributed form-factors allows the children to move around (while interacting with the toolkit modules,) and hence engage in physical play. While *Unruly Splats* uses foot-sized buttons placed in the environment (on the floor,) the modules in *Scratch Nodes* are hand-held and are carried around by the users. In *DIO*, we use a comprehensive BLE-based wireless network to support modules that can placed in the environment, can be held in hands, or can be worn as wearables by multiple children.

2.3 Learning with Constructionist Toolkits

The age-group of children that we targeted with our toolkit is 8-12 years. This age group in Piaget' classification is defined as the *concrete operational stage* [41]. This is when children start to develop logical thinking, and learn to reason. This reasoning though, as Piaget notes, is limited to concrete situations, i.e. thinking about hypothetical situations can be difficult for the children of this age. Using the components of a construction toolkit to create artifacts of personal significance is an important goal associated with constructionist learning [43], as described in the previous section. Doing this can require the children to connect the toolkits' components (and their associated functionalities) to hypothetical situation from their everyday lives, a process that involves abstract thinking.

We relied on *scaffolding* [36] to assist this process. Scaffolding is based on Vygotsky's theory of *zone of proximal development(ZPD)* [57], which is an area of learning that occurs when a student cannot do a task on his own, but can do it when assisted by someone with a higher skill set. Scaffolding is the guidance received by the children to help them work within this ZPD. It describes how adults can model the process of a learning-based task given to children and can provide support to make them do more than what they would be able to do otherwise. This support is gradually reduced, leaving the students to master the skill on their own.

Past work on construction toolkits provide descriptions of constructions that the participants are able to make using the toolkit [4, 30, 38]; but the process to take them to that stage is usually missing. During the pilot studies for *DIO*, we had noticed that participants facing difficulties in applying their learning to abstract problems (as established by Piaget). Hence, we used a scaffolding-based approach to support them. Specifically, we borrowed the techniques of *reduction in degrees of freedom, demonstration,* and *discussion,* from the literature on scaffolding in education [2, 55, 56], and applied them to making and learning with constructionist toolkits. We describe these techniques and their implications as observed during our studies.

2.4 Collaborative Learning

Collaboration is a synchronous activity that is the result of a continued attempt to construct and maintain a shared conception of a problem [47], through which learning occurs socially [52]. Collaborative learning takes place when a group of people perform an activity together through different forms of interaction mechanisms such as *awareness* and *grounding* [62]. *Awareness* is the ability to observe people's behaviour or changes to an object resulting in transfer of knowledge [14], while *grounding* helps in achieving collective actions. Prior work in evaluating collaborative learning has established that children prefer to work together in small groups [26, 27], resulting in increased engagement, enjoyment and motivation towards the activities [26, 49]. Work done by Ed Hall [16] in demarcating distance zones based on interpersonal distance in social interactions is an important phenomenon in the context of social interactions called *proxemics*. The four zones are described as *intimate, personal, social* and *public*. A recent survey conducted by Yu et al [61] on computational kits for young children highlight the lack of kits designed for collaborative learning.

Interactive collaborative systems embody typical characteristics as identified by Hornecker [23] namely: *embodied constraints and access points. Embodied constraints* refer to the configuration of space and objects. Work done by Eden et al [11] in evaluating their setup demonstrate that constraints such as sharing of resources and spatial orientation fostered group awareness and cooperation. *Access points* enables users to manipulate relevant objects and provide control to the users. Stewart et al check how children collaborate while using a conventional desktop with one mouse versus using tangibles which allow multiple users to interact at once [53]. Multiple input devices allow simultaneous action and easing active participation.

DIO supports collaboration by enabling multiple children to conceptualize, program and then test things out in groups. Children can use multiple modules together and share them amongst themselves, enhancing the opportunities of mutual interactions. Our user studies are designed in such a manner that the children have to divide the task at hand requiring them to coordinate and plan. Due to the tangible nature, being aware of what others are doing is easy and enhanced by the wireless nature since the modules can be placed anywhere. Owing to the distributed design of the toolkit, children can place the modules on their body and in the environment. This enables them to allow or block access to certain modules depending on their placement. A child can place a module on his body, in their *personal space* while another one can place it on the wall, in the *social space*. A similar interaction is observed in [35], wherein children adapted different strategies to stop others from accessing objects and fight for control. Using our toolkit, children are able to experience interactions based on interpersonal distance. Closest to our work, Torino [54] is a physical programming language which supports collaborative learning between children with mixed visual abilities.

3 DIO: A TOOLKIT TO ENABLE SHARED, MULTI-USER CONSTRUCTIONS

Our toolkit comprises of hemispherical modules providing a variety of input, output functionalities. Equipped with dedicated attachments, these modules can be suspended in a variety of configurations on children's bodies or in the environment. We built an augmented reality based programming application that runs on a smartphone, and allows the users to link the input, output modules to form combinations. For instance, a button input can be linked to a bulb output module such that he bulb lights up whenever the user presses the button. The user first locates the modules through the AR interface, and then links them together by drawing a virtual line on the screen. The phone is able to identify the modules through the distinct computer vision based patterns put on their 3D enclosures. A robust wireless communication topology including connections between the modules and the phone, and within the multiple modules, ensures that the users' actions create the required data-communication channels — like from the button to the LED as in the case discussed above. Now, we discuss our design process, implementation of each part in more detail.

3.1 Formative Study: Workshop-style Design Session

In order to comprehend what children understand regarding the concepts of input and output, their perceptions of body, environment mounted modules, we conducted a workshop-style design session with 16 children (5 girls, 11

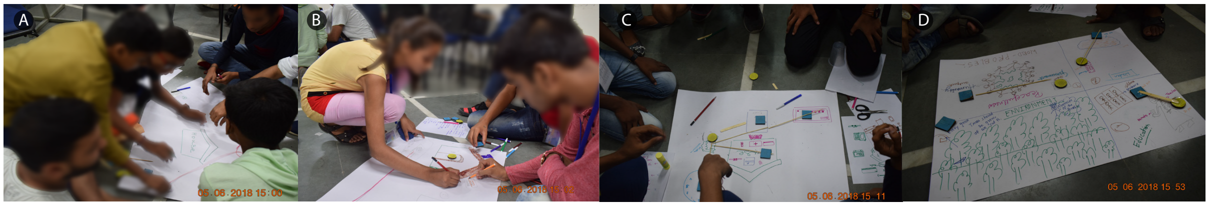

Fig. 2. Formative study observations: Constructions made with low-fidelity material

boys; ages 9-13) at a primary school in New-Delhi, India. Three facilitators began the session by introducing the children to the ideas of input and output by referring to common examples from their everyday lives. The abstract ideas were explained using physical manifestations: blue square and yellow circular card boards representing output and input modules respectively; that the children could wear on their bodies and suspend into the environment. We induced the theme of *supernatural powers* to trigger imaginative usage scenarios. The card board modules could let the children sense anything, or cause any kind of action. They were prompted to use these super powers for everyday scenarios like "designing a smart home," "helping their mother," or "making their city a better place to live." We had included other low-fidelity materials (like paper charts, prototyping sticks) to facilitate exploration. The activities of children during the workshop were recorded for future analysis.

Children made a wide variety of designs ranging from an "anywhere door", to "smart electronics and furniture", to a "time machine". They had critical ideas for environmental conservation such as water harvesting, pollution reduction and prevention of deforestation (see Figure 2). In most of these designs, children placed input on people to sense their feelings and thoughts and output on people as well as other things in the environment to necessitate actions for the latter. Many interesting designs came across these two approaches – a girl placed an input module on herself and the output on her friend, explaining that her friend would sense her feelings and come to see her whenever she wanted to; another boy put an output on a clock to stop it according to his wish; one team placed the input module on the citizens of the country and and output on the government as they wanted to monitor the deeds of people. The designs highlighted children's perception of body and environment mounted input and output modules, and hence helped take important decisions regarding the design of the toolkit. For instance, in multiple constructions, children used a multitude of inputs to control an output; this led us to define the *adder* module to serve this purpose. Similarly, the design of *attachments* was inspired by how and where children wore the modules on their bodies. Finally, children envisioned the use of input, output to sense, express emotions; which motivated the design of *emotion display* module.

3.2 Module Design

The *DIO* module comes in form of a hemisphere dome of diameter 36mm with all the electronic circuitry fitted inside it (see Figure 3.A). The electronic circuitry consists of two parts: (i) main board, all the modules have the same main board; (ii) functionality board, different modules have different functionality board depending on the sensing or actuation functionality that they provide. The functionality board is placed on top of the main board as shown in the figure. The module is powered by a 440 mAh (rechargeable) battery arranged at the bottom of the module.

The main board provides basic computing and communication abilities to the modules using a . It is circular in shape with a diameter of 34mm. It contains a Redbear BLE Nano 2[1] (Bluetooth low energy ready microcontroller) along with the necessary circuitry printed on a custom-made printed circuit board (PCB). The main board connects

1 https://redbear.cc/product/mb-n2.html, Accessed 15th February 2019

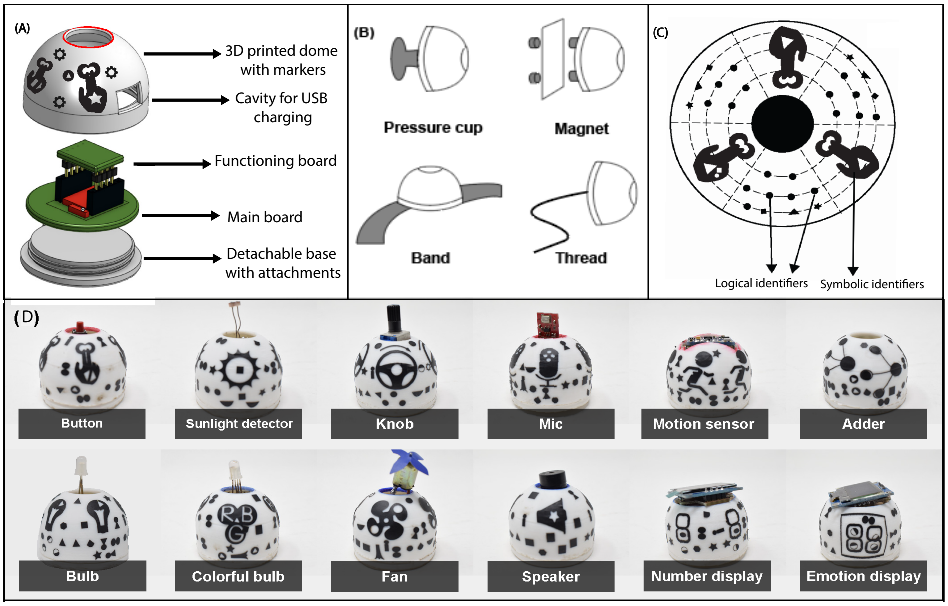

Fig. 3. A: Module Design; B: Attachments; C: Final Marker design; D: DIO modules [Input: Button, Sunlight detector, Knob, Mic, Motion sensor; Adder; Output: Bulb, Colorful bulb, Fan, Speaker, Number display, Emotion display]

to the functionality board through two rows of 4-pin female headers, connected to GPIO, power and ground pins from the microcontroller. This makes the main board scalable to accommodate any type of functionality board (included the currently implemented modules or the newer modules that can be developed in future.) The functionality board provides the input and output capabilities to the modules.

The casing of the module includes a detachable base that connects to the hemispherical part through screw-based mechanism. The base comes with different kinds of attachments (Figure 3.B,) used to mount the modules on the body or in the environment. The pressure cup attaches to flat surfaces like walls, the magnet attaches to magnetic surfaces, the band is used to wear the module on the hand or on the head, while the thread can be used to mount the module in a variety of ways — like say hanging it from the ceiling. The *DIO* toolkit includes 5 input modules, 6 output modules, and an *adder* module 3.D). All input modules have a red colored ring on their top, while the output modules have a blue one, to enable easy differentiation by the children.

3.2.1 Input Modules: These modules provide sensing capabilities to the toolkit. An input module can control multiple output modules at the same time. Inputs included in the toolkit are: button, knob, sunlight detector, microphone and a motion sensor.

3.2.2 Output Modules: These modules provide actuation capabilities to the toolkit. An output module can be controlled by only one input module in a simple pairing. Outputs included in the toolkit are: bulb, colorful bulb, fan, speaker, number display and an emotion display.

3.2.3 Adder Module: Adder module enables multi point input-output pairings in which a combination of multiple inputs determines the output. Depending on the type of inputs connected to the adder, different pairings fetch different output. If two digital inputs (like *button*, and a *sunlight detector*) are connected, the adder computes their

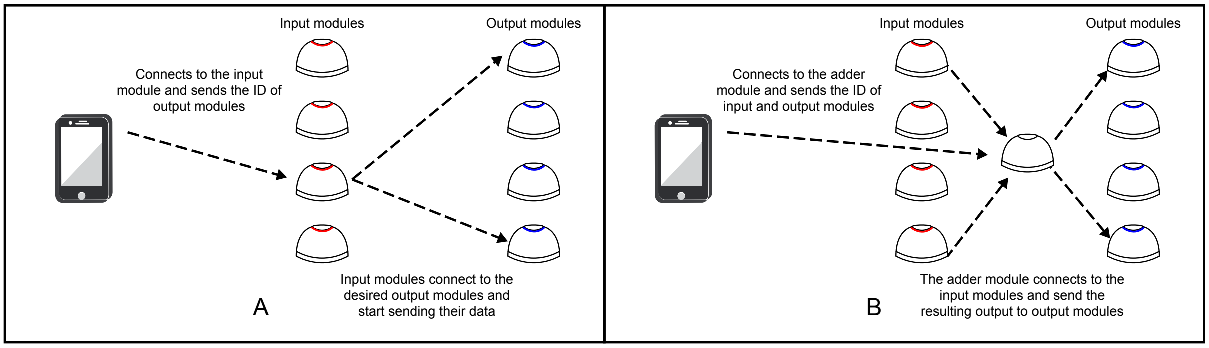

Fig. 4. Communication topology [A: Adder module not used; B: Adder module used]

logical AND, and transfers it as the output. If two analog inputs (like *knob*, or *microphone*, or a *motion sensor*) are connected, the adder computes the greater value among the inputs. Finally, in case of an analog input, and a digital input, the adder transfers the value from the analog input if the digital input is high.

3.3 Module Programming

All communication between the smartphone, input modules, and output modules takes place though the Bluetooth Low Energy (BLE) protocol. The input modules are programmed to receive commands from the smartphone asynchronously, which contains information about which output modules they should connect to or should disconnect from. The output modules advertise themselves until connected to an input module, after which they listen to the input data and control their respective output accordingly. Any BLE communication happens between a *BLE Central* (master) and a *BLE Peripheral* (slave) [2]. Input modules behave as BLE Peripheral while communicating to the smartphone (the smartphone being the BLE Central,) and as BLE Central to communicate with the output module; that act in the peripheral role (see Figure 4.A). The topology is different in case of an adder (see Figure 4.B). When a user links an input module to an adder (using the AR based interface,) the smartphone communicates with the adder instead of the input module, sending it the identification of the input that it has been linked to. Similarly, once the adder is linked to an output module, its identification is also sent to the adder. Subsequently, the adder module acting as a BLE Central, connects to both the input as well as the output module (both acting as peripherals,) and communicates with them to transfer data from the input to the output. BLE functionalities on the Redbear BLE Nano 2 modules were implemented using Apache MynewtOS[3], which enables the BLE central and peripheral roles of the microcontroller.

3.4 Augmented Reality based Application

The Augmented reality based application was developed in Unity 3D, and utilized Vuforia SDK to implement the computer vision (CV) based recognition of the modules. Modules are recognized based on the distinct pattern added onto their enclosure. The modules needed to be recognizable from different angles, to be programmed while being mounted into the environment or on to the bodies of children; hence we designed the modules to be dome shaped, with the pattern covering the curved, top surface. Existing work on implementing patterns for CV based detection was limited to two-dimensional surfaces [6, 29]. A critical part of our implementation cycle was to design the three-dimensional dome shaped patterns from scratch. Figure 3.C shows the final pattern design.

[2]https://www.embedded.fm/blog/ble-roles, Accessed 15th February 2019
[3]https://mynewt.apache.org/, Accessed 15th February 2019

Fig. 5. AR Application [A: Scanning the modules [i: Back button; ii: Augmented button (input); iii: Augmented colourful bulb (output); iv-v: Button to switch between back and front camera view]; B: Front camera view ; C: Connecting modules by making a line (vi)]; D: Home Screen; E: Feedback Screen [ix: Feedback, x: Next step] ; F: Instruction Screen[xi: Back button, xii: Current level; xiii: Next step]]

The pattern is divided into six sectors of 60 degrees each. Each alternate sector is used for *symbolic identification,* — to indicate the input or output module type to the users (figure 3.D), while the other three sectors are used for *logical identification.* — to provide feature points for encoding data regarding module identification by Vuforia SDK. The nine feature points can have 1 of the 5 possible shapes – circle, triangle, semicircle, star or square, creating distinct identification for each toolkit module.

An augmented reality object is rendered on the mobile device as soon as a module is identified and scanned. Figure 5.A shows the rendered objects corresponding to *button* input and *colorful bulb* output modules. The user can swipe, "form a line" between the rendered objects to create an input to output pairing as shown in figure 5.C. The application also provides the option of switching to the front camera to enable the user to scan the module attached on his/her body with ease 5.B.

We designed a *demo mode* to teach the children regarding the usage of the application (figure 5.D-F). The mode consisted of four steps: locating and scanning an input module, locating and scanning an output module, making a "line" between the two modules, and triggering the input to observe a change in the output. At each step, the app provided the child with an instruction(figure 5.F, and waited for him/her to perform the appropriate action. The child was given a feedback (figure 5.E) in case a wrong action was detected, like when an output module was scanned in place of an input module or the line was drawn in the opposite direction, etc. The process was designed such that the child could work with it alone without any assistance from the researchers or any other adult.

4 PILOT STUDY

To gain preliminary understanding of how children would work with *DIO* toolkit and to uncover any usability issues, we conducted a pilot study. The findings from this study were used to refine the final toolkit design before the evaluative studies. The study was conducted with 9 children (3 girls, 6 boys; ages 9-13) in a public school in New Delhi, India. Essentially, we tested the *demo mode* of our AR programming tool with the participants. Each participant was given 4 (randomly selected) input, output modules and a smartphone running the DIO application; he/she had 15 minutes to try out the demo mode. Three participants could work at once based on the available number of smartphones. Children were allowed to work alone; 2 study facilitators were around in case the children faced any problems.

4.1 Observations and Results

Though the application was received well by the participants, there were some issues that need to be solved.

(1) **Native language support:** Our application had information only in English and we noticed that three children faced difficulty in comprehending the text. We introduced another mode to incorporate Hindi language to help children understand the instructions.
(2) **Video instructions:** Some children did not read the textual instructions and consta ntly tapped on the UI elements on the screen. Informed by this experience, we switched from text-based instructions to visual/video based guidelines in the application. We added demo videos at each step to help the children better understand the context in comparison to text-based instructions.
(3) **Inclusion of symbols in marker design:** Prior to this pilot study, our patterns for computer vision based recognition included logical identifiers only. We had hypothesized that the children would be able to recognize the modules based on input, output component that protruded out of the casing or by looking at the AR object rendered on to the module after it was scanned. However, post this initial study we re-designed our patterns to include symbols such that children could recognize module functionality in first inspection.
(4) **Other minor issues:** Out of the 16 modules, a few modules stopped working with wireless communication or discharged batteries. We rectified these issues before the evaluative studies.

5 EVALUATIVE USER STUDIES

We conducted two user studies to evaluate our toolkit regarding the six research goals as specified in section 1. Both studies were conducted with a different set of participants at a public school in New Delhi, India. The participants were recruited through sign-ups via school procedures. An IRB (Institutional Review Board) approval was taken prior to conducting the studies. Figure 6 shows the activities conducted during the two studies. Both user studies provided cues regarding common research goals R.G. 1, R.G. 4-6, i.e. *usability*, *development of associated concepts*, *subjective factors*, and *collaboration*. The first user study specifically checked regarding R.G. 2 that is *problem solving using DIO*, and hence included a design challenge session. Similarly, the second user study checked regarding R.G. 3 that is *what do children make using DIO*, and hence included an open-ended design activity. We used a mixed method analysis to analyze the observations from these studies. We analyzed session videos, performance in demo mode, design challenge activities; conducted artifact-based interviews; summarized responses in pre-study and post-study questionnaires. Next we describe each user study in detail.

5.1 User Study 1

The study was conducted with 9 children (4 girls, 5 boys; ages 9-13); participants were selected to be different from the pilot study to avoid any biasing. The study lasted 2.5 hours and was completed in two sessions, before and after the lunch break at the school. Three facilitators (F1, F2, F3) conducted the study and remained available throughout the duration. The first session comprised of a pre-study questionnaire (15 minutes), an introduction to DIO toolkit (15 minutes), and demo mode activity (45 minutes). The pre-study questionnaire inquired regarding the participants' demographics and their prior experiences with constructionist toolkits or electronics in general. The facilitators distributed the questionnaires to the children and waited until they were completed. Post that, F1 introduced the *DIO* toolkit to the children through a PowerPoint presentation. We used the example of a young boy named *Ramu* who learned to program the modules using the smartphone application. The video showed

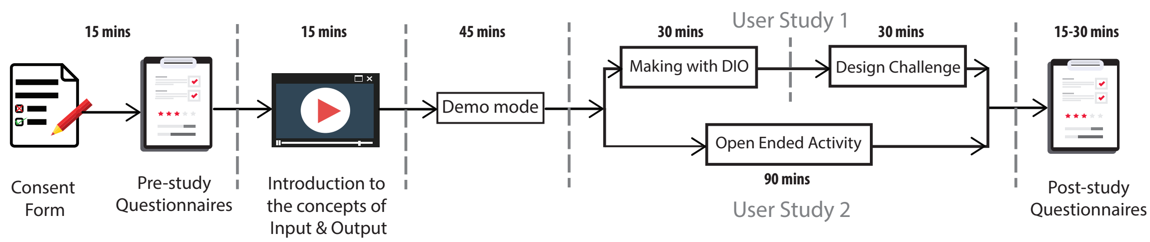

Fig. 6. User Study 1 and 2 Design structure

Ramu performing different steps like: finding an input module by locating the red ring, finding a specific modules by looking at the symbolic pattern, finding the output module and programming the modules by a "making a line." The video showed Ramu's fingers pointing to the feature that we wanted the children to pay attention to at each step, like the red ring, etc.

This was followed by the demo mode session; we conducted the session in a way different from the same in the pilot study. The 9 participants were divided into 3 teams, and the 3 children of each team worked with the demo mode together sitting close around a small table. Each child still had his/her own input, output modules and a smartphone, but could also see what the other team members were doing. We had arranged this to observe trends of collaboration (R.G. 6,) i.e. how the children would develop a shared understanding of the programming interface. Kendon et al. have suggested that a shared transaction space provides shared focus and awareness [32]. We maintained this focus on collaboration and hence the team formations during all proceeding activities of the user study. However, post the demo mode stage, the 3 members of a team shared a smartphone among themselves as opposed to each child using his/her own one.

The session after the lunch break included a *making with DIO* session (30 minutes), a design challenge (30 minutes), and post study questionnaires. In the former, we introduced the children to all toolkit modules; facilitator F1 presented different modules in an iterative manner and demonstrated their functionalities, facilitators F2, F3 worked with the different teams, helped the children make connections, video recorded their perceptions of the modules, etc. We also introduced the children to attachments at this stage. In the design challenge session, the three teams were given design problems that they had to solve using the *DIO* modules. Figure 7.B shows the problems and their solution using *DIO* modules. We selected three different problems to facilitate knowledge sharing in the end; problems were assumed to be of similar difficulty as they all required 1 input, 1 output module.

After sharing the design problems, the teams were allowed to work alone. They were required to approach a centrally located table at specific times, like once they have an idea and need modules for implementation, or when they were facing some problem and needed help. This is when they had an interaction with facilitator F1 who responded to their requirement(s). These conversations were video-recorded for future analysis. For instance, we maintained a count of instances when either of the teams approached the table with a problem, or had a wrong idea, or perhaps the right idea. Once the teams were ready to implement, the F1 asked the children to pick the modules that they required, and observed if they were able to identify the modules via the symbolic patterns. Finally, the teams were asked to present their construction to others.

5.1.1 Observations for Research goal R.G. 1: Usability of the system. All participants were able to complete the demo mode within the allotted time (mean: 8 min, max: 12 min, min: 5 min). They successfully scanned the modules, and formed connections by learning through the instructional videos at each step. Though trying it out for the first time, children were able to develop a good understanding of how the AR application worked. For

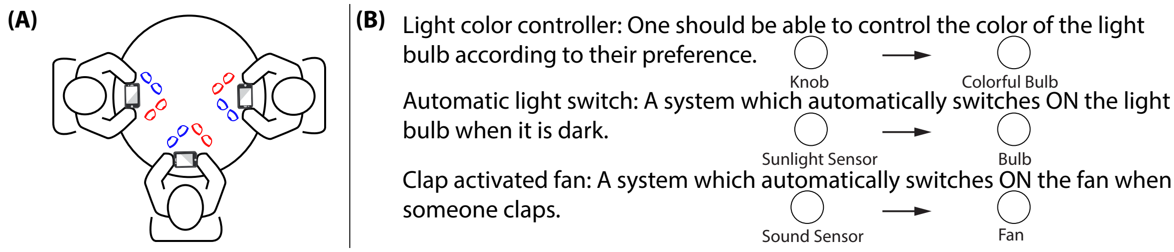

Fig. 7. A: Seating arrangement during the demo mode session, B: Problem statements for design challenge session

instance, they were able to manipulate the distance between the phone camera and the modules to maintain appropriate zoom level for the modules to be recognized. They learned that the recognition was faster on some sides of the modules than the others, therefore, in cases when recognition was taking time, they rotated the modules to reveal other sides of the pattern to the phone. While making a connection, some children tried to make a line before the modules were scanned, while few others tried to make a line from the output module to the input module. After a few iterations, learning from the corrective feedback provided through animations, they realized the problem, and successfully completed the task. As initially hypothesized, we observed children helping one another to work through the demo mode. We report all such finding related to collaboration in the discussion section.

5.1.2 Observations for Research goal R.G. 2: Problem solving with DIO. All teams were able to solve their respective design challenge and implemented in using *DIO* modules (completion time: 5, 10, 17 minutes). All 3 teams initially approached facilitator F1 after discussing the solution within themselves. While, the approach described by team 1 and team 2 matched the expected solutions (figure 7.B), the one provided by team 3 didn't. In response to their design challenge of detecting a clap, they suggested the idea of holding a button module between the two hands, such that the button would be pressed while clapping. However, on further discussion with the facilitator, they realized that the button in their hands will fall while clapping, and hence their solution will fail; This led the team to quickly come up with the idea of using a microphone instead of the button module. While trying to recognize the modules based on the symbolic patterns on their enclosure, team 1 picked the knob module correctly, but got confused between the colorful bulb and the bulb module; they identified the correct module with help from facilitator while team 2 and team 3 correctly identified their modules on their own. Children were able to use attachments to wear their constructions and presented them to others.

After providing the solution to the design applications, the teams had to recognize the modules using the patterns on the surface and pick them up to implement their solution. Team 1 picked the knob module correctly,but got confused between the colorful bulb and the bulb module. They asked the facilitator for help to identify the correct module and then chose the right module. Team 2 and Team 3 correctly identified their modules and started connecting them using the phone. All the teams built their constructions and presented their projects to each other.

5.2 User Study 2

The study was conducted with 12 children (3 girls, 9 boys; ages 9-12); we could not work with participants from user study 1 due to logistic issues, hence selected new participants from the same school. As before, we divided the participants into 4 teams of 3 children each. This study lasted 3 hours and was completed in two sessions.

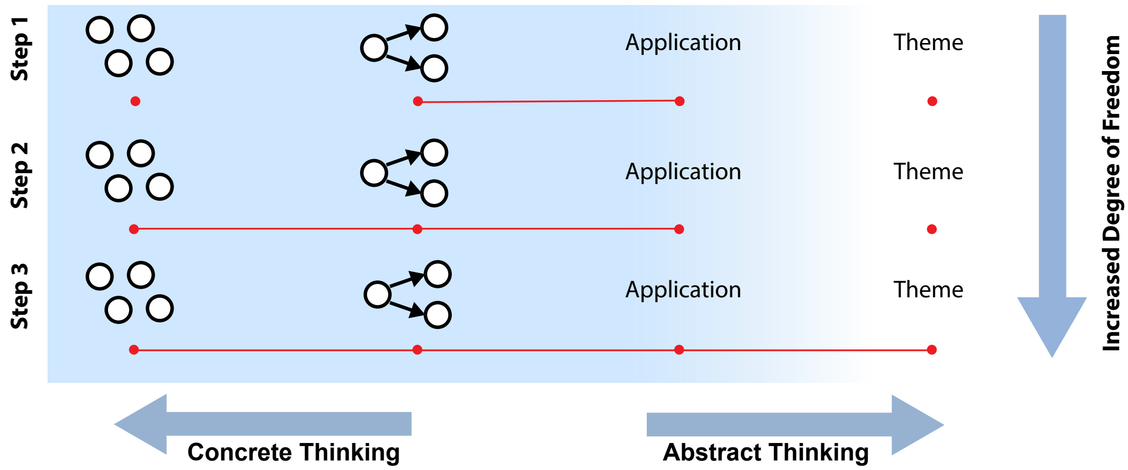

Fig. 8. Social Scaffolding in making with construction toolkits

The first session was same as that in user study 1 (introduction and demo). The second session included an open ended design activity (90 minutes) and a post-study questionnaire (30 minutes).

Open ended design activity required the participants to design artifacts of personal significance; doing this is an important goal of constructionist based learning [39]. This process however requires the children to associate the toolkit modules and their functionalities to the scenarios of their everyday lives, the problems that they face, etc. Here, we describe a *scaffolding based approach* that we used to assist the young participants in this process. Piaget has established that children of the target age group face challenges in such tasks that include forming connections to abstract concepts like everyday scenarios [41]; hence, our designed approach supported this activity through *reduction in degrees of freedom, demonstration,* and *discussion* techniques [2, 55, 56]. Reducing degrees of freedom means to simplify the task by reducing the number of constituent acts required to reach the solution. Demonstration means to show the learners an example solution (and the procedure of getting to it) for the task that they are being asked to solve. Finally, discussion means that the learners are given time to process the new ideas and information, by discussing them with their peers. Figure 8 shows the proposed approach. We sought to assist the participants in using the *DIO* toolkit in constructing solutions around different themes from everyday life. The transition from the toolkit modules to the application themes is one of increasing abstract thinking; the modules and their functionalities represent concrete concepts, something that the children can see and can manipulate, while the application themes are highly abstract concepts.

The process aimed to transition the children across this difference (from concrete to the abstract) in a step-by-step manner, while gradually increasing the degrees of freedom. Four facilitators F1, F2, F3, F4 worked with one team each and facilitated this process for the children. In the first step, children were given a set of modules (pre-decided by the facilitators to support simple constructions,) and were prompted to simply connect them together. After completing this construction and experiencing the resultant interactive functionality, they were prompted to find a suitable application for the functionality they had designed. It can be noted that while the modules and the resultant functionality were pre-decided, coming up with a potential application was left on the children. We hypothesized that having a concrete functionality enabled by the construction present with them would make it easier for the children to connect it to an application. Children implemented a different application

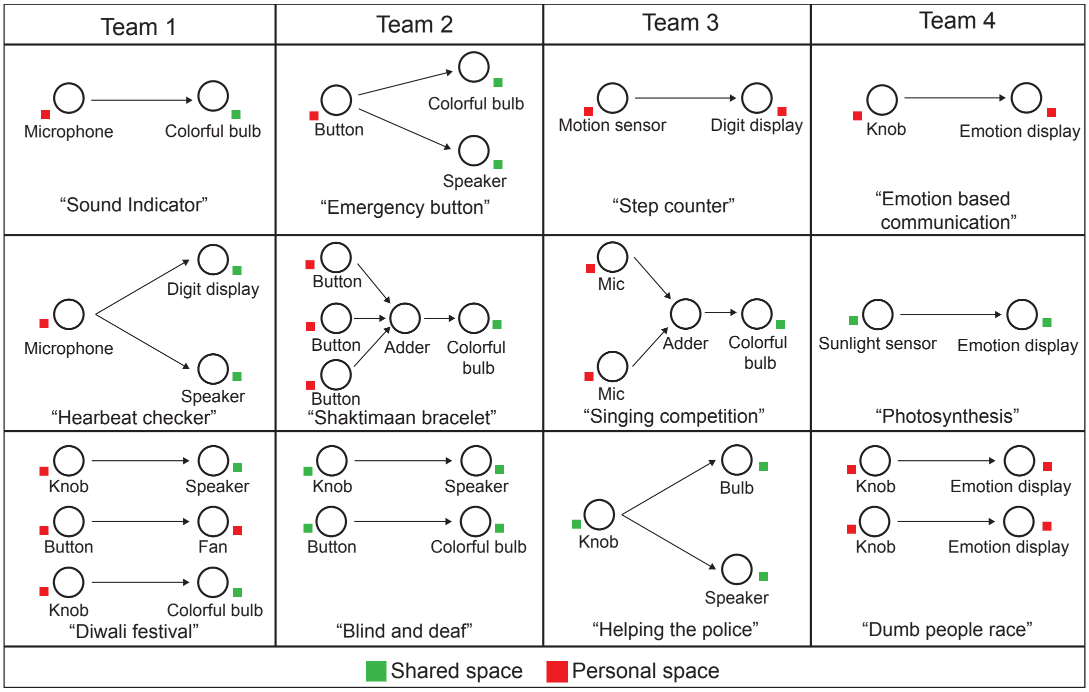

Fig. 9. Summary of Completed Constructions

using *DIO* modules in the second step; they were prompted to base their thinking on the application completed in the previous step, and come up with a new application. In cases when the children remained too biased towards previously completed constructions, the facilitators encouraged them to brainstorm more such that the new application would require some different modules, rather than just the construction completed previously. The aim at this step was to take the children from toolkit modules to an application (see figure 8). The experience from the first two steps was used as a demonstration to assist in the final step; children were asked to create solutions to personally meaningful problems, and were prompted to consider how they had implemented solutions for two applications in the previous steps. They were still provided with overarching themes to provide some direction to their thinking; the themes were selected to be open, encompassing a multitude of design possibilities, hence preserving the open-ended nature of the activity. The themes given to the four teams were: "Festivals", "My Delhi, Smart Delhi", "Helping the police" and "Making a game."

The post study questionnaire included 4 set of questions (shown in figure 11). The first set prompted the children to identify 4 modules by looking at their symbols; they also had to answer if the modules provided input or output functionality. The second set aimed to check regarding participants' understanding of 4 toolkit elements, specifically sunlight sensor, motion sensor, adder module and the attachments. This was followed by a set of questions to test the participants' ability of applying the concepts of input, output (sensing and actuation) to hypothetical problems from their everyday lives. Finally, we included questions to check regarding the subjective factors, like what did the participants liked (or disliked) in the workshop, or what was their favourite DIO modules, etc. Children were given 30 minutes to answer the questions. The facilitators asked the questions verbally in case the children faced difficulty in comprehending them in written formate.

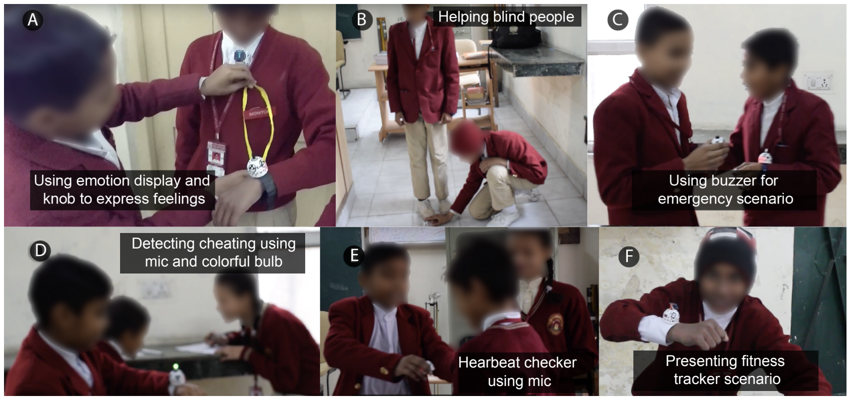

Fig. 10. Children presenting their constructions

5.2.1 Observations for Research goal R.G. 3: What do the children make? Figure 9 shows the constructions completed by the teams during the open ended activity; the three rows correspond to the constructions completed during the three steps. Step 2 constructions were adapted from the ones completed in the first step; we first discuss those followed by constructions from the third step. **Team 1** started with a microphone and a colorful bulb module; Once the two modules were connected, the bulb glowed whenever a (sufficiently loud) sound was heard. The team utilized this functionality as a *sound indicator* to help their teacher check regarding silence in the classroom while she was away. Children imagined a scenario of an examination, wherein the microphone was attached to a wall within the classroom, and the bulb was worn by the teacher on her wrist. They explained how the "teacher would know in case someone cheated in the exam." During the step 2 when asked to think of another different application, the team adopted the microphone to create a "heartbeat checker" to assist the doctors. The microphone was attached on the chest of the patient and sensed his heart beat. The team connected the microphone output to a number display and a speaker module enabling the doctor to see and hear the heart beat pattern.

Team 2 started with a button and a colorful bulb module. They used the construction for an "emergency button" application for themselves in case they got lost — separated from their parents while visiting a crowded place, etc. When enacting the scenario, a child wore the button while another child (parent) wore the colorful bulb on his wrist. The child pressed the button to notify his parent when he got lost. The team asked for a speaker which they also connected to the button; the speaker would make sound when activated and the parent would be able to find the child via this sound. During the second step, the team expanded the application to multiple children. All children wore an emergency button and notified *Shaktiman*, a superhero from popular Indian comic. The button modules were fed into an adder which was connected to the colorful bulb worn by the superhero.

Team 3 started with a motion sensor and a numeric display module. Once the modules were connected together, the system was able to count the number of times the sensor was moved. The team used this functionality for the 'step counter." Post this, the facilitator had helped the children realize how they could use an adder module to compare the step counts of two children, and implement a race scenario; during step 2, the two expanded this functionality to design "singing competition." Two children wore the microphones on their wrists and sang into the modules by raising their arm close to their mouth. The colorful bulb was attached on the wall and "displayed who was winning." Essentially, the colorful bulb displayed red or blue color depending on the amplitude of the voice inputs collected by the microphones, which the children use to judge who was singing better.

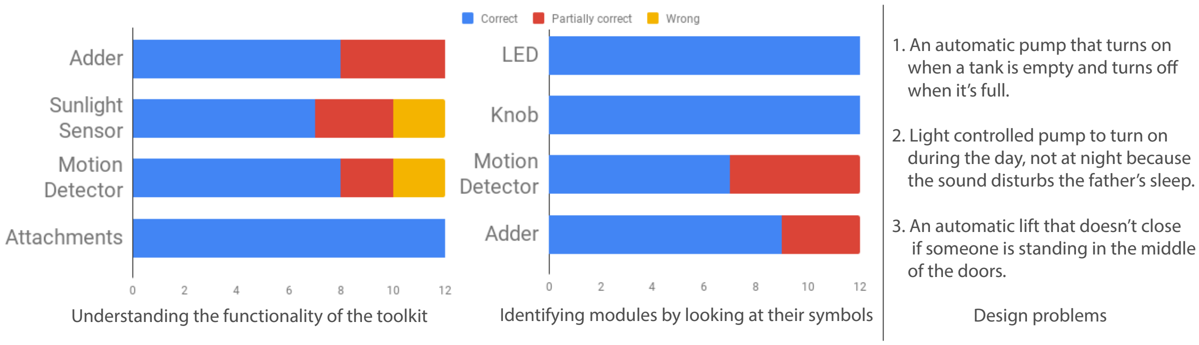

Fig. 11. Post study Questionnaire: Questions and observations

Team 4 started with a knob and an emotion display. Once the modules were connected, the knob could be rotated to show 4 different emotions on the display. The team used this construction for "emotion based communication," to express their emotions to their cousin living in a different city (*Patna* as per the story of one participant from the team). During step 2, the team expanded this functionality to visualize the emotions of plants during photosynthesis. One child became the plant, wore the emotion display module on his hand and connected it to a sunlight sensor module. During demonstration, "children explained how the plant became happy when seeing the sun." It is noteworthy that they used the camera flash of a phone to test their construction (rather than the actual sunlight).

In the step 3, the experience developed in the previous steps was utlized to construct around a theme. Team 1's theme was ***Festivals***. They selected Diwali, one of the biggest Indian festivals for their implementation. They used a colourful bulb, a buzzer, a fan, a knob, and a button for their design construction. Diwali is a festival of lights, and hence the children decorated their house using the colourful bulb and changed the light colour using knob. On this day, children burn crackers to mark the victory of good over evil. They demonstrated this idea using a button and a buzzer; the buzzer when activated by the button produced sound as that of a cracker. They celebrated the festival very happily. However the next day, they realised that the pollution level had increased drastically and tried to lower it down by using a fan. They controlled the wind (intensity) of the fan using the knob, and cleared away the dust particles. They finished their presentation by giving a message to not burn crackers on Diwali.

Theme for team 2 was ***My Delhi, Smart Delhi***. The common assumption that comes to our mind when we think of a Smart City deals with ideas of automated luxuries. However, this team interpreted the notion of Smart Delhi with devising a way to help the disabled, specifically blind and deaf people. They helped the blind navigate in space using a button and a buzzer. The button was placed close to any points of danger and activated the buzzer in case the blind user was near. Similarly, they alerted the deaf using a knob and a colorful bulb; the different colors of the bulb were associated to different activities for example, red for danger, and blue for safe.

Theme for team 3 was ***Helping the police***. They role-played the scenario of a house where a thief comes to steal the money from the safe. They used a knob, a bulb and a buzzer for this project. They used visual representation of the knob to replace it with the knob of the safe. They connected it with the buzzer and the bulb. As soon as the thief rotates the knob of the safe, the alarm begins to glow and the bulb lights up. The police is indicated of the burglary and they reach in time to catch the thief.

Finally, team 4's theme was ***Making a game***. They enacted a race among dumb people. Their idea was that the dumb are unable to express their emotions as they cannot speak. So, they wanted to help them convey their

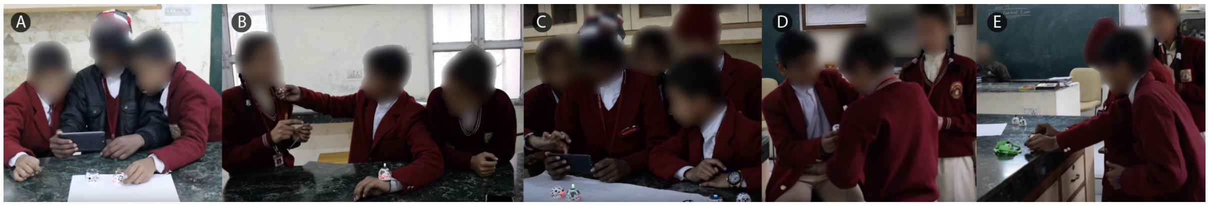

Fig. 12. Collaboration themes [A-C: Children working collaboratively to program and test out DIO modules; D: Child A (on the left) helping Child B (on the right) to wear DIO module on the body using attachment; E: Children working towards present their construction to the class]

emotions with the help of the emotion display and the knob. After the race, every participant expressed his/her emotions, i.e., whether he/she is happy or sad or neutral on the emotion display by rotating the knob.

5.2.2 Observations for Research goal R.G. 5: Subjective factors. Overall, all participants enjoyed the workshop as per their answers from the post-study questionnaire. When asked about what specifically did they like, most common answers were about the modules and the application (or the phone). 4 participants appreciated the role of facilitators. For instance, one participant wrote that he liked how the facilitators "were involving in the workshop and helping everyone." Two participants liked that they learnt new things, while another one mentioned that he learnt to work in a team. When asked about what they disliked about the workshop, 10 out of 12 participants gave answers like "No," "Nothing," or "No and Never". 1 of the remaining participants didn't like when the app crashed, while the other one complained about the modules not connecting at times. The answer to which module did they like the most, the answers were split. 4 participants wrote colorful bulb, 3 mentioned the fan, and others said sunlight sensor or display or mic the adder. 2 of the participants liked all the modules. Anup wrote "my favorite module is every module as they do different work."

5.2.3 Observations for Research goal R.G. 6: Collaboration themes. In this section, we report on the collaboration themes that we had observed during the two user studies (see figure 12). In the demo mode session, 3 children sat around a table and each explored the AR app through a smartphone and an independent set of modules. We took some noteworthy observations: The children constantly peeked into the activities of one another, discussed among themselves to *mutually* complete the demo mode. Participants ahead in their progress across the demo mode were seen helping others while the ones lagging behind asked for assistance. We saw children trying to scan other's modules on their phones to see what appears and draw comparisons with what they could see using their modules.

In activities other than the demo mode, children shared the smartphone among themselves i.e. within every team, hence leading to different collaborative behaviour. During these times, children took turns to engage in programming activity while making the construction. If a construction consisted of multiple input-output pairings, each team member took turns to connect one input-output pairing and passed the phone to the next member. Even when a child was programming, other children found, engaged in other parallel activities like rotating the modules for better scanning (figure 12.A). After a connection was formed, each member explored the input-output pairing, activating the input to observe the corresponding change in the output (figure 12.C). Apart from forming constructions, presenting them to fellow participants was an important step in the user study procedure. During this time we observed children sharing different tasks: planning; making props to enhance presentation ; wearing modules, mounting them into the environment (figure 12.B,D-E). We observed children to take shared ownership of their designs; they worked together to complete them and described them with pride.

6 DISCUSSION

In this section we ground our observations in relation to the greater literature on constructionist learning. We further highlight the design implications for future research in this domain.

6.1 Understanding the DIO Toolkit and Concepts behind the Internet-of-Things

An essential part of the DIO toolkit experience is the act of programming, i.e. to connect input and output modules to create different interactive applications. Children were able to understand the notion of the input module affecting the functionality of (or controlling) the output module, as apparent in the applications that were constructed, and in how they interacted with those (like triggering the input, expecting a change in the output, etc.). When asked to elaborate on how the system was functioning, they explained the connection between the input and the output in terms of known technology paradigms like "an invisible wire," or a WiFi connection. In some cases, they formed newer, unique explanations to describe the functionality; when asked to describe the functionality of a *sunlight sensor* controlling a *bulb*, child A explained that the sensor "takes energy from the sun like a plant and powers the bulb." Children had also understood the role of programming in forming this connection, and explained it as "making a line between the modules," motivated from the design of the AR application. This lead us to hypothesize the role of the AR based programming interface in helping the children form such simplistic understanding of the system. The *direct* mapping between users' actions (making a line) and the corresponding system functionality (wireless connection forming between the modules) might have played an instrumental role in such transparent understanding of the overarching concept. This is different from GUI based interfaces wherein this mapping is broken, as the users program on the screen and not in the physical space which the modules lie in.

Children were also able to clearly articulate the specific roles of different modules in the toolkit as apparent from the results of post-study questionnaire (figure 11). When asked whether the *adder* was an input or output, more than half of the children responded with "none," or an "X" (wrong), while others didn't answer. Coming to specific functionality of different modules (like *sunlight sensor*), children had a good grasp of that as well; the related questions were also answered well. Moreover, the many creative ways in which they used these modules to imagine new applications hints at good understanding. However, we noticed that in some cases, the understanding of a module was based on the specific scenario in which it was used. Future studies can motivate more tinkering with the modules, especially trying them in different scenarios, etc., to curb this limitation.

Some children also faced some difficulty in understanding the functionality of the *adder* module. When asked to describe it in the questionnaire, most children wrote something around that "it connects many inputs with many outputs." However, an *adder* is required only when multiple input modules are involved; the number of outputs having no effect. We noticed a similar mistake during the making activity when the children used the *adder* to connect single input with multiple outputs, though it was not required. We designed the *adder* module to provide functionality to deal with multiple inputs, depending on what the inputs were — like acting as a logical AND for two digital inputs, a *comparator* for two analog inputs and so on. Researchers of systems developed in the past had pointed out that small children face difficulty in differentiating between modules that enable such special functionality (*modifier* blocks [30],) hence a multi-functional adder would be beneficial. Given the perception of children from our evaluative studies, future designers can go a step ahead by keeping the *adder* as a standard module that necessarily goes between input and output modules and intelligently forms various functions, hence reinforcing a general *input-adder-output* mapping for the young users.

Finally, children were able to understand the use of attachments to attach the modules on to the body or in the environment. Where the modules were attached was decided by children' understanding of *personal space (PS), social space (SS)*, the specific requirement of the application. All inputs except the *motion sensor* was used in both PS and SS, while the *motion sensor* was used in the PS only. When attached in the PS, the input catered only to the child who wore it, like the *button* in *Shaktiman bracelet*. When in the SS, the input could be accessed by everyone or catered to environmental sensing (like *sunlight sensor*). The *motion sensor* was for physiological sensing and hence was only connected on to the body, in PS. The case of the *Heartbeat checker* application was especially interesting. Therein the doctor used a *microphone* module to sense the heartbeat of his patients. The module meant to be used for all patients was attached to the patient's body in his PS (to enable physiological sensing) and then was kept back on the table. It is interesting to note how the children were able to make sense of the affordances of different input modules — like body-based physiological sensing of *motion sensor*, *microphone* as a *Heartbeat checker*, — and chose to place them accordingly. The output modules were kept in both PS and SS, similar to the inputs. Like in case of the inputs, the users considered the affordances of the modules to decide on their usage in the application. For instance, the *bulb* and the *speaker* both being placed in PS, were used differently. In the *Emergency button* scenario the *bulb* was used as a notification to the user wearing it (the parent of the child in an emergency) while the speaker was used to notify everyone around the child. Hence, the children well understood the notion of *personal space (PS), social space (SS)*, and had manifested those in their applications.

6.2 Usability of the AR Interface

Overall it was observed that the children were able to use the augmented reality based interface to program the modules. Moreover, they were able to understand the limitations of the implementation like faster recognition on some sides of the pattern, etc. and adapt their usage based on that. In the recent past researchers have used AR for enhancing education applications, specifically to provide informative digital feedback to user's interactions in the physical world [13, 28, 33]. Our toolkit leverages AR technology to not only provide a digital feedback in the application, but also as a programming interface to connect the modules together. As a result the users had to interact with the toolkit in both the physical and digital domains. Though this design created new affordances it also had a few limitations for the system. There were times when children got confused as to when to switch between the two mediums. For instance, after programming in AR environment, they sometimes did not interact with the modules physically to explore their functionality; they instead tried tapping on the augmented object of an input module in AR itself expecting that the output would show a change.

6.3 Making with DIO Toolkit

Papert had established that the best learning experiences happen when the children are involved in designing things that are meaningful to them [39]. The themes that emerged in the user studies were regarding helping people (especially the disabled), and to save the environment. In the scenarios related to the disabled people, the children role-played those people and showed how their constructions helped them by making their environments safer or by let them express themselves better. Similarly, the *Diwali festival* constructions involved the children bursting eco-friendly crackers (supported by DIO modules) and "cleaning pollution using *fan* module." Interestingly, environmental protection had also emerged as the major theme during the formative study, though that study was conducted with a different set of children, from a different government school in Delhi, India.

A notable feature of the constructions completed during the user studies was their *imaginative* character. Many of them were not functional designs and could not be used in the scenario that they were designed for. Instead they were abstract representations of the solutions to these problems that the children wanted to solve, and hence were valuable. For instance, the design of the *microphone* module could not actually be used as a *Heartbeat checker*, but rather represented the children' intent to help the doctor in his (otherwise manual) inspection of his patients. Similarly, it might not be feasible to place many *button* modules in the environment to help the blind, but was a solution to a significant problem. Moreover, this imaginative solution can be made practical by replacing the *button* modules with another spatial input sensor. So in a way, the DIO toolkit allowed the children to be imaginative, and to go beyond the technical functionaliy. This relates to the definition of *expressivity* (through construction toolkits) as defined by Resnick and Silverman [43].

We argue that the distributed design of the toolkit made it have *wider walls*, and a *high ceiling*, and hence triggered such imaginative problem solving scenarios. Children could imagine the standalone, attach-able input, output modules of the toolkit to exist in a variety of physical settings: in indoor living environments of house or classroom, on walking pathways (to help the blind,) outside the house (during *Diwali* celebrations,) and on their bodies, hence making them usable in different lived contexts. Overall the toolkit, with its distributed design and rather simplistic sensing, actuation functionalities could fit within *natural settings* as perceived by the children, and hence triggered their imagination and creativity. In future, researchers can aim to design toolkits that further integrate into settings pertaining to the users' lived experiences, to increase expressivity in this manner.

6.4 Collaboration through DIO

We observed a variety of collaboration themes as mentioned in section 5.2.3; the themes can be divided in relation to *programming* and *non-programming* activities. The ones related to programming can further be classified to be based on two different scenarios, wherein the collaborating children have *individual smartphone* and *shared smartphone*. The former was the case during the demo mode, while the latter was the case during other activities. During programming, the smartphone becomes the primary *access point* [23] allowing the children to connect the modules together. Collaboration was observed whether this access point was individually held by each child or was shared between three children. In the former case during the demo mode, the visibility of the *DIO* tangible modules and common activity context were sufficient to enable collaboration; children collaborated to make sense of the mobile application together and engaged in shared construction of knowledge. In other cases when the access point was shared, children utilized turn-taking to collectively work with the modules. Turn taking is an important skill in a social setting and children do not learn it quickly [58]; it worked well during our user studies. Programming using tangible blocks has been observed to cause collaboration due to multiple access points [19], in case of *DIO*, a shared smartphone, shared tangible modules, combined with effective turn taking were able to support similar collaboration practices. We hypothesize that this method of utilizing single, shared access point for programming might be more especially more effective in enabling collaboration between >3 children.

Once the programming is done, i.e. during non-programming activities the input, output modules provide the many access points; herein the notions of personal space (PS), social space (SS) become significant. In section 6.1 we have discussed how the participants placed their modules in PS, SS to restrict, enable access for others. Apart from mounting modules using attachments, children sometimes kept them free, passed them around (to other children) like in case of *heartbeat checker* or during the demo mode. Overall, the flexible design of the modules, including attachments to mount on the body/environment allowed many possibilities for spatial arrangement of modules, hence enabling different *embodied constraints* [16, 24] for collaboration.

Research has demonstrated that collaborative learning enables higher achievement and productivity, foster supportive relationships, and social competence among children. Despite these benefits, not many constructionist toolkits are specifically designed to be used by multiple users at once [37]; the recently developed wearable platforms for instance are worn on by a single child, who uses them to build applications of personal significance [9, 30]. DIO, owing to its design features allows multiple children to work together on problems of shared motivations and purpose. Resnick has established the importance of working with peers to support constructionist learning, emphasizing their role to provide *inspiration* and an *audience* [44]. By enabling children to work together, DIO can effectively support a third, critical role of a *design partner*, in addition to the other two. In our observations, we have explained how the team members assumed shared responsibility of the constructions that they worked on. Future researchers can take cues to design toolkits that support all three roles, extending towards a potentially beneficial, social dimension in constructionism.

7 FUTURE WORK

As discussed above, DIO, owing to its distributed design and unique affordances to support collaboration, can help further the advantages of constructionist toolkits. Moreover, our scaffolding-based approach can inspire conceptualization of a process to engage children in working with such toolkits, to help meet the learning goals; herein, we expand on these different possibilities.

Distributed form-factor of the toolkit including the standalone modules allowed the children to easily integrate DIO in their environments. Newer modules with other sensing, actuation capabilities, and a greater variety of attachments can further assist this effect; Allowing children to conduct explorations in other settings like in a playground can motivate newer usage scenarios. Another interesting direction is to think regarding virtual variants of the DIO modules that provide sensing, actuation in virtual-physical environments within augmented and virtual reality; the resultant toolkit designs can extend expressivity afforded by physical modules, and can become useful as these new media become more feasible. Considering DIO modules as a 'design material' can produce exciting opportunities as well: Researchers can consider the form of modules to be inspired from the functionalities that they enable, or the applications that they are to be used for, looking beyond a single shape, like the dome in the current effort. In this regard, it might be advantageous to borrow cues from current research on smart materials.

Researchers can explore other forms of collaboration activities that can be supported through the current form-factor of DIO or other variants. One can update the design such that every user has his/her own smartphone, while the system tracks and maintains an account of the connections made by all users. Apart from supporting programming, the AR interface in this setting, can indicate regarding the visibility of other users and can signify the modules occupied by others. Another similar variation is to enable remote collaboration across distance. The design can be updated to include a new toolkit module (say *location module*) to transmit DIO signals (as triggered by the users) between two locations through Wifi communication. Such modifications can further expand the functionality of DIO in supporting collaborative making for children.

We have illustrated the importance of our user study procedures including the scaffolding-based approach in introducing the young users to the toolkit, assisting them within the zone of proximal development, and in enabling collaboration. Researchers can further explore these different roles that adults can play in supporting constructionist learning. They can contribute guidelines for conducting different activities like brainstorming and making, to reach standardized methods for facilitating children's usage of such toolkits.

8 CONCLUSION

DIO is a novel digital-physical toolkit to enable constructionist learning for children from age group 8-12 years. Through self-sufficient, dome-shaped modules with an embedded assortment of input, and output capabilities it allows children to co-construct multi-user wearable as well as environmental interaction creations. The programming is facilitated through a simple AR-based programming application leveraging novel and unique 3D identification patterns present on each module. We further present our learnings from the iterative design approach we followed and share guidelines with the hope of inspiring further explorations in this exciting space of constructionist learning initiated by Seymour Papert decades ago.

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