Exploring Opportunities to Aid Generation of Input Action Ideas for Tangible User Interfaces

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Novice tangible interaction design students often find it challenging to generate input action ideas for tangible interfaces. To identify opportunities to aid input action idea generation, we built and evaluated a tool consisting of interactive physical artifacts coupled with digital examples of tangible systems and technical implementation guidance. Through video recorded design sessions and interviews with twelve students, we investigated how they used the tool to generate input action ideas, how it supported them, and what challenges they faced. We found that the tool helped in generating input action ideas by enabling to experience input actions, supporting hands-on explorations, and introducing possibilities. However, introducing examples at times caused design fixation. The tool fell short in supporting the planning of technical implementation of the generated ideas. This research is useful for tangible interaction design students, instructors, and researchers to apply in education, design similar tools, or conduct further research.

CCS CONCEPTS • Human-centered computing~Interaction design~Systems and tools for interaction design • Human-centered computing~Human computer interaction (HCI)~Interaction techniques • Human-centered computing~Interaction design~Empirical studies in interaction design

Additional Keywords and Phrases: Tangible interaction design, Input actions for tangible user interfaces, Tangible user interface design tool, Idea generation

1 INTRODUCTION

Tangible interaction design (TIxD) involves designing tangible user interfaces (TUIs). TUIs involve physical artifacts that represent digital information and serve as interactive controls of the computational media [73]. Such interfaces enhance interaction with computational applications by building upon users' knowledge and skills of interacting with their physical environments [34,39,66]. They enable users to perform various physical actions (e.g., squeeze, stretch) as input actions to interact with digital information [31,34]. Research that emphasizes the benefits of TUIs exists in a wide range of domains such as education [5,6], music [4,10], health [3], and sports [37]. Researchers have identified various strengths of TUIs, such as the ability to facilitate tangible thinking, epistemic action, and external representation [66].

TIxD courses introduce students to TUIs (e.g., definitions, history, examples), conceptual frameworks, theoretical underpinnings, application areas, strengths and weaknesses, and design principles and methods [65,84,85]. [34,73] lists three key design requirements of TUIs – 1) Computational coupling of tangible representations to underlying digital information and computation, 2) Embodiment of mechanisms for interactive control with tangible representations, and 3) Perceptual coupling of tangible representations to dynamic intangible representations. Our work focuses on the second design requirement with the objective to support the generation of input action ideas. Direct manipulability of digital information using one's body is a crucial aspect of TUIs [34]. It is through input actions that TUIs leverage users' sophisticated haptic skills and utilize bodily engagement as a crucial component of interaction with technology.

A challenge in TIxD is to seamlessly extend affordance of physical objects into the digital world [36]. Moreover, since the physical objects play the dual role of control and representation, the physical embodiment somewhat limits the input action possibilities that designers can incorporate in the objects [34]. In our previous study [9], we found that novice TIxD students often find it challenging to generate input action ideas. They usually restrict their explorations to familiar possibilities such as input actions usually found in everyday devices (e.g., press buttons, touch, rotate). Doing so may lead them to potentially ignore other input actions that may address the design problem better. These common input actions are a limited set of human's rich motor abilities and dexterity [41]. [17] points out that although these common input actions, being simple to carry out physically, are designed to ease the products' use, they shift the load from motor skills to the cognitive domain. There exist TUIs and physical tools to aid idea generation in non-TIxD domains [27,38,67] as well as certain TIxD aspects such as application of framework [29], conceptualization of transformation [51,52], and prototyping [2,11,63]. However, little has been done to support input action idea generation. There are only a few design guidelines for designing input actions for TUIs (e.g., [12,34]). To our knowledge, IdeaBits [9] is the only design tool to aid generation of input action ideas for TUIs. We designed IdeaBits for novice TIxD students, and it consists of interactive physical artifacts coupled with digital examples of TUIs and technical implementation guidance.

In this paper, we present IdeaBits 2.0, which is an iteration of the original IdeaBits system [9]. We designed and developed it as an exploratory research instrument to identify potential ways of supporting novice TIxD students to generate input action ideas and things that should be avoided. We define novice TIxD students as those learning TIxD for the first time and with no prior experience of the domain and similar domains that involve embodied interactions (e.g., gestural interfaces). We evaluated IdeaBits 2.0 by conducting an exploratory case study that involved video recorded design sessions, remote observations, and semi-structured interviews with twelve novice TIxD students individually. We investigated how the participants use IdeaBits 2.0 to generate TUI ideas, how it supports them, and what challenges they face. We found that IdeaBits 2.0 helped in generating input action ideas by enabling them to experience the input actions, encouraging and facilitating hands-on explorations, and introducing possibilities. However, it fell short in supporting the planning of the technical implementation of the generated ideas. Also, introducing examples at times caused design fixation. Based on our findings and existing literature, we derived a set of design guidelines for tools to support idea generation of TUIs, including how to enable experiencing input actions, encourage and facilitate hands-on exploration, facilitate prototyping, and provide examples and technical implementation guidance. The contributions of our work are 1) IdeaBits 2.0 as an open-sourced tool [72], 2) design and results of an exploratory case study for evaluating IdeaBits 2.0, and 3) design recommendations for tools to aid novice TIxD students in generating input action ideas. This research will be useful to TIxD students, instructors, practitioners, and researchers to apply the learnings in TIxD education and practice, design similar tools, or conduct further research on this topic.

2 BACKGROUND

2.1 TUIs and Physical Tools to Aid Idea Generation in Non-TIxD Domains

TUIs and physical tools such as cards exist to aid idea generation in specific contexts and various non-TIxD domains, which are found to be beneficial from their evaluations. Here we discuss a few of these tools, while a detailed review of such tools can be found in [22,57,80]. There also exist a few tools to aid idea generation in the TIxD domain, which we discuss in the next section. Jaasma et al. [38] designed Blue Studio, an interactive space for multi-stakeholder idea generation sessions. They found that the set of physical objects acted as binding anchors for reflective thinking. A similar exploration was done by Smit et al. [67], who designed a diverse set of physically interactive objects, Ideating in Skills toolset, to support multi-stakeholder idea generation sessions. They found that the objects' ambiguity and unfamiliarity triggered users' imagination, curiosity, and physical exploration. Trotto et al. [70] designed six interactive tangible tools for idea generation. They found that tools with open-ended and undefined interaction possibilities along with unpredictable outputs encouraged exploration of the interaction possibilities. In contrast, tools with a precise aim reduced attention to the interaction possibilities and resulting output. Although none of the tools discussed above were developed with a focus on TIxD, most of them seem to be extendable to TIxD, which can be explored in future work.

2.2 Design Tools for TIxD

There exist TUIs and physical tools to aid with certain TIxD aspects such as application of framework [29], conceptualization of transformation [51,52], and prototyping [2,11,63]. However, to our knowledge, IdeaBits [9] is the only tool (not yet evaluated) to support idea generation of input actions (more details in the next section). Another tool that comes close to supporting generation of input action ideas is the P.bot activity developed by Analytis et al. [2]. It is a creative design activity involving generation of input action and prototyping; however, it is limited to designing interactive cardboard robots. The authors found that it helped to increase engineering students' knowledge and confidence in electronic prototyping. To our knowledge, IdeaBits [9] is the only design tool to aid generation of input action ideas for TUIs. We designed IdeaBits for novice TIxD students, and it consists of interactive physical artifacts coupled with digital examples of TUIs and technical implementation guidance.

Research on TIxD suggests the importance of iterative and rapid prototyping to obtain correct input-output mapping [30]. In turn, other researchers have designed tools to facilitate prototyping TUIs (e.g. [11,51,52]) and found them to be beneficial from their evaluation. Bdeir [11] designed littleBits, an opensource library of electronic components assembled in small circuit boards, which can be snapped together to build prototypes. The author found that participants, who were otherwise skeptical of their electronic prototyping skills, were comfortable in prototyping using littleBits. Parkes et al. developed two motion prototyping toolkits for actuated products - Kinetic Sketchup [51] and Bosu [52]. They found that the ability to limit mechanical complexity by isolating elements in Kinetic Sketchup facilitated envisioning transitions. Experimenting with a variety of material and motion qualities by using Bosu helped novices understand the physical world while challenging assumptions related to kinetic behavior and inspired diverse ideas.

2.3 Role of Examples in Idea Generation

In the context of design, inspiration is the process of evoking creative solutions with an entity's help [18]. One way of providing inspiration is through examples. Designers highly value inspiration [19,28] and frequently search for it [28]. They also collect examples for inspirational purposes [44] and generate ideas by building upon existing solutions [18]. Other researchers have, however, found both positive [14,25,71] and negative [40,59,71] impact of examples on idea generation; which is dependent on various factors such as format of the examples [7,13], number and variety of examples [48], similarity of the example with solution space [16,71] (exception [25]), time of presenting the examples [71], participants' domain [59] and level of expertise [13,14], and type of problem statement [14] among others. Next, we illustrate the effect of some of these factors by discussing a few studies.

Researchers have studied inspirational stimuli in the form of images. Casakin [14] studied the positive impact of inspirational stimuli by providing an assortment of images from architectural and remote domains. He found that both experts and novice architectural designers benefitted when solving ill-defined problems. In contrast, only experts benefitted when solving well-defined problems due to the absence of instructions to use analogies. Researchers also studied inspirational stimuli in the form of text. Tseng et al. [71] studied the impact of textual descriptions of products on undergraduate mechanical engineering students. They found that closely related stimuli, compared to distantly related, helped generate more novel ideas when presented before participants began solving the problem. Distantly related stimuli helped generate more functionally distinct and novel ideas when introduced after, compared to before, participants began solving the problem. The ideas generated involved functional principles of the presented stimuli in all the cases. Researchers have suggested ways of minimizing as well as taking advantage of design fixation. For example, Jansson et al. [40] found that providing sample designs led the designers to incorporate both positive and negative aspects of the samples. In turn, Purcell et al. [59] suggest avoiding example designs that involve flaws and taking advantage of design fixation by providing examples of innovative design solutions.

Among the various formats of inspirational stimuli and examples, images (e.g., diagrams and photographs) have been widely studied [14,40,54,59], followed by text [25,71]; while other formats (e.g., video and sound), as well as the combination of formats (except for image with text), have been relatively less studied. Although other researchers have studied the role of physical products as inspirational stimuli [38,67,70], they rarely investigated design fixation (exception [70]). In our study, we provided examples in the form of interactive physical objects and in video, image, and text formats. Also, despite extensive prior research on this topic, the effect of examples on idea generation for TUIs has not yet been thoroughly investigated.

3 IDEABITS 2.0

We designed IdeaBits [9] as a tool to aid novice TIxD students in generating input action ideas for TUIs. It consists of two sets of artifacts – physical-only and sensor-enabled. Each set involves five artifacts to enable users to experience a set of input actions (squeeze, stretch, bend, fold, and pull). For each of these input actions, IdeaBits provides two TUI examples that incorporate the action. These TUI examples are shown on the graphical user interface (GUI) of IdeaBits using video, images, and a link to the published paper (Figure 1). The GUI involves two types of pages: 1) a home page that displays images of the sensor-enabled artifacts (SEAs) as clickable buttons, and 2) example pages that show the TUI examples, which can be opened from the home page. These examples are provided to help users conceptualize the introduced input actions as a part of TUIs. The difference between the SEAs and the physical-only artifacts (POAs) is that interacting with the SEAs opens the linked TUI example page and can be further interacted with to play or pause the video. IdeaBits provides technical implementation guidance through a "Tech" button on the GUI for each input action. The button is hyperlinked to Sparkfun [86] pages that provide information on the sensors involved in the SEAs. The intention is to help users generate technical implementation ideas for input actions.

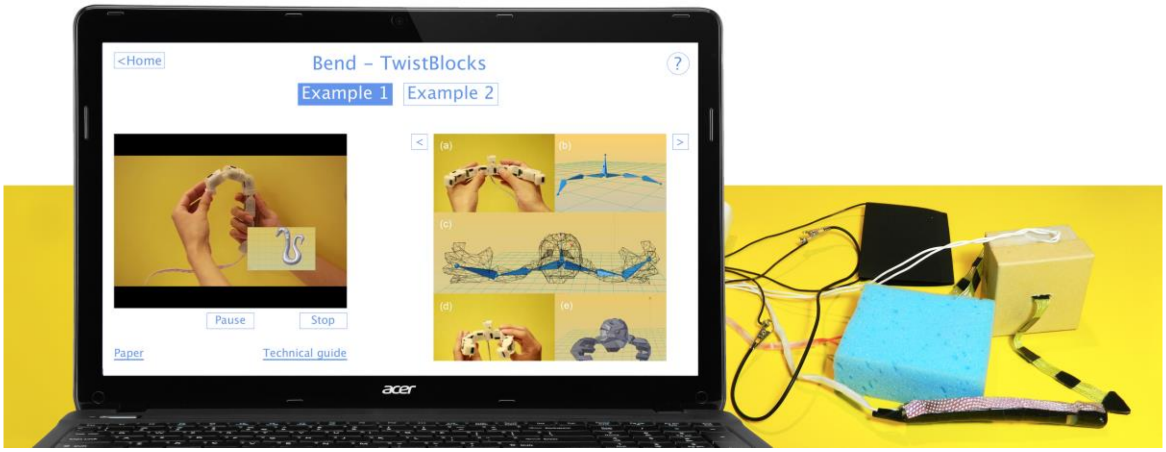

Figure 1: GUI (left) and SEAs (right) of IdeaBits. The TUI example shown on the GUI is TwistBlocks [76].

3.1 Design Process of IdeaBits

To design IdeaBits [9], we followed a non-linear process with four inter-related components - 1) ideation and conceptualization; 2) interviews to understand TIxD practices; 3) participation in a TIxD course; and 4) prototyping of Idea Bits. In this paper, we add to the details of this process beyond what is published in [9] by elaborating how the input actions, output, and TUI examples were selected.

3.1.1 Selecting Input Actions

To decide which input actions to introduce through IdeaBits, we cataloged sixty-two existing TUIs' input actions by reviewing publications from the proceedings of the top conferences for TIxD - CHI and TEI. From the catalog of twenty-eight input actions [8], we chose the final five based on several factors. To open the design space for users, we chose input actions less frequently found in TUIs and not found in everyday devices. Also, other researchers have found that common examples cause more design fixation than unusual or novel ones [56]. We chose input actions for which we could provide video, images, and paper of two TUI examples. Since the videos were not usually available in the conferences' library, we contacted the authors or searched on video streaming platforms such as Youtube [87]. We chose input actions involving easy technical implementation for ease of building IdeaBits and to not intimidate the users (being novices) through the provided technical guidance. We chose input actions with possibilities for variations to enable users to modify when incorporating them in their ideas. For example, variations of stretch involve stretching say a rubber band using two fingers of a hand or two hands. We chose input actions which were simple and involved relatively low physical effort so that users could do them easily without discomfort or having to perform complicated physical activities. We also avoided input actions that could potentially damage the artifacts (e.g., tear, punch).

3.1.2 Design Rationales for TUI Examples, Output of SEAs, Technical Implementation Guidance, and Design Guidelines

To minimize design fixation (based on findings from [14,75]), we chose TUI examples that would introduce identifiable variations of the input actions in the SEAs. To avoid design fixation, as suggested by [40,59], we ensured that none of the examples belonged to the solution set of the design task used in the user study to evaluate the tool.

The TUI examples illustrated real-world application scenarios of the SEAs' input actions. To hint users towards this connection between the SEAs and the TUI examples, we designed the output of the SEAs as opening of the associated TUI example page on the GUI. To facilitate interactive explorations, we extended the SEAs' interactivity by enabling users to play or pause the videos.

We provided technical guidance by introducing the electronic components used in the SEAs. We used available sensors (e.g., flex sensor and pressure sensor), instead of multiple raw electronic components (e.g., resistors and capacitors), in the SEAs to avoid reducing users' (especially being novices) creative confidence (as found by [62]) and to introduce them to modular components which are found by [11,62] to be beneficial in electronic prototyping.

The objective of IdeaBits 2.0, aligned with Osborn's [49] guidelines for generating ideas, was to help generate as many ideas as possible (preferably diverse) without worrying about their value. Hence, we chose not to provide design principles as they may limit users' creativity by triggering them to judge their ideas. Even though not all the generated ideas will be good, designers can next select and refine the promising ones to align with TUI design principles.

3.2 Design Process of IdeaBits 2.0

After prototyping IdeaBits, we informally evaluated it through a heuristic evaluation [46] conducted by the first author (who is not a TIxD expert), feedback from the second author (an expert researcher and an experienced instructor in the TIxD domain) on the complete tool, and feedback from a peer TIxD researcher (Master's degree in visual communication design) on the GUI. We next describe the revisions we made along with our design decisions and rationale.

3.2.1 Artifact Revisions

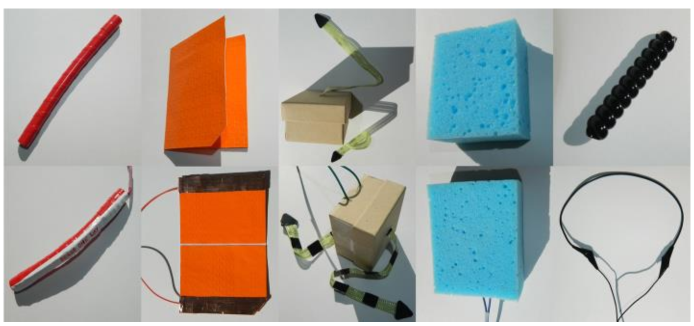

Figure 2: POAs (top) and SEAs (bottom) of IdeaBits 2.0 for bend, fold, pull, squeeze, and stretch (left to right) input actions.

Physically testing the artifacts of IdeaBits revealed that the bend SEA was rigid, making it difficult to bend. We replaced the glue stick used to make the artifact with a thinner one and covered it with a more stretchable tape. Three of the SEAs in IdeaBits were black (Figure 1). In IdeaBits 2.0, we made the artifacts within each set different in color to help users distinguish between them. We also made the pair of artifacts associated with the same input action of similar material and visual look (Figure 2).

3.2.2 GUI Revisions

We changed the video player's design to match the design of popular video players, such as in YouTube [87], which users would already be familiar with (Figure 1,3). To ease studying the videos, we provided color-coded bars across the video's timeline to denote different sections. We used red, green, and blue color-codes to denote system overview, input action, and implementation, respectively. Users can click on any of the bars to jump to that section of the video. The paper format of the TUI examples in IdeaBits was provided through a hyperlink of the web address. In IdeaBits 2.0, we enabled viewing the papers within the GUI, without having to jump to the web browser. It also enabled us to use color-coded underlining (code consistent with the video format) to help users quickly find information in the papers. We added thumbnails and captions for the examples' image format to ease browsing and understanding of the images. More images and the sitemap are provided in Appendix A.1.

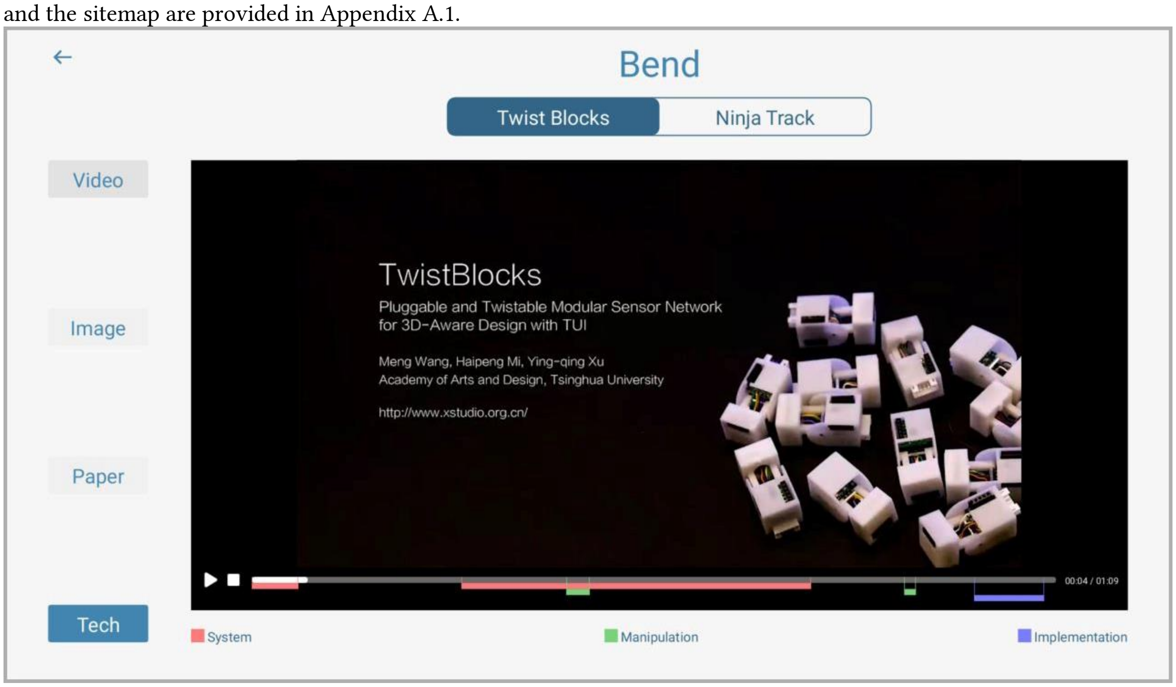

Figure 3: Video format of TUI examples in IdeaBits 2.0 (bottom). The TUI example shown is TwistBlocks [76].

4 USER STUDY METHODOLOGY FOR EVALUATING IDEABITS 2.0

We conducted an exploratory case study [83] to identify ways in which potential support can be provided to novice TIxD students to generate input action ideas and things that should be avoided. We investigated target users' interactions with IdeaBits 2.0 and their experiences while considering the tool as only an exploratory attempt rather than a promising solution. The research questions (RQs) that we addressed are 1) In what ways do users use IdeaBits 2.0 to generate TUI ideas?, 2) In what ways do users think IdeaBits 2.0 supports them to generate TUI ideas?, 2.1) In what ways do users think IdeaBits 2.0 supports them to generate input action ideas?, 2.2) In what ways do users think IdeaBits 2.0 supports them in planning the technical implementation of the generated ideas?, and 3) What challenges and limitations do users face while using IdeaBits 2.0 to generate TUI ideas? The motivations behind our RQs were to identify users' needs during the idea generation process (RQ1), contribution of the components of IdeaBits 2.0 (RQ2), and opportunities to build tools better than IdeaBits 2.0 (RQ3). The evaluation consisted of video-recorded individual design sessions where the participants used IdeaBits 2.0 to generate ideas for TUIs addressing a given problem statement. The first author remotely observed these sessions, at the end of which she conducted semi-structured interviews.

4.1 Participants, Setting, and Research Materials

We conducted the study with twelve novice TIxD students (eight undergraduate) from the School of Interactive Arts and Technology (SIAT), Simon Fraser University, screened using a questionnaire (Appendix A.2). The participants were of the age group of 18 to 44 years old, including six males and six females. The first author conducted the study in a lab at SIAT. We provided IdeaBits 2.0, including both sets of artifacts so that the participants could use whichever they preferred. We also provided some stationery and modeling materials (Appendix A.3). The first author designed a 60 minutes timer app [88] (developed by a peer researcher), which had a visual timer with voice reminders at 40, 20, and 5 minutes remaining. We ran this app on a tablet during the design sessions to help the participants keep track of time.

4.2 Procedure and Tasks

We conducted the evaluation individually with each participant. For each evaluation session, first, we conducted an introductory session of 15-25 minutes, where the first author provided the participants an overview of the session, explanation of the design task, and introduction of IdeaBits 2.0 while they tried it out. She showed TUI examples of only one input action while encouraging them to interact with only one artifact from each set. She mentioned that they were expected to use the prototype but were not limited to the introduced input actions and examples. She then conducted the 60 minutes design session during which the participant was left alone in the room to do the given design task. During the design session, the first author did remote observation from a different room by live-streaming the video. She noted, including start and end timestamps, what they were doing (building prototype, sketching, etc.), what they were using (which artifact, modeling material, etc.), and how they were using it. She also noted any technical malfunctioning instances and anything unexpected that stood out in relevance to our RQs. Based on her observation, she expanded the interview questionnaire with open questions to probe for reasons behind certain observed behaviors. Following the design session, the first author conducted semi-structured interviews for 14 to 25 minutes to investigate how they used IdeaBits 2.0 to do the design task and their experience. We provide the interview questionnaire in Appendix A.4. We compensated the participants with $25 cash.

The design task was to "Generate ideas for a tangible system, involving one or more physical objects, which you can use to communicate how you are feeling to a partner/friend/family member over distance. The system should enable him/her to receive the feeling you communicate as well as communicate back theirs. It should also enable you to receive the feeling s/he communicates to you." Participants were asked to choose at least three emotions from the six basic emotions given as part of the task: happy, sad, scared, angry, disgusted, and surprised [20]. To maintain uniformity among the participants and avoid any implicit assumptions, we mentioned during the introduction that they could use any input actions and were not limited to the five introduced possibilities. We made this decision based on our findings from the pilot study, where almost all the participants assumed that they were limited to the introduced possibilities since they were asked to use the tool during the design session. Only some of them questioned the first author during the introduction to verify this assumption. However, we did not ask participants to avoid design fixation since such instruction would impact and bias the results. Participants were required not to involve emoticons in their ideas due to their common use for communicating emotions [61]. They were asked to generate many ideas and select one final idea to fill four deliverables - 1) Sketches or rough physical models (without electronic components) with optional description, 2) Written description of how their idea supported communication of emotions over distance, 3) A table listing the emotions they could communicate using their idea along with the corresponding input actions they required to perform on their idea and the resulting output, and 4) A list of the electronic components they would need to build a prototype of their idea. The design task sheets are provided in Appendix A.5.

We designed the task focusing on enabling exploration of the input action. We chose emotion since they are abstract and natural to be linked with physical actions, while they do not have any default associations. The input actions would be richer than input actions for control or concrete representations. Moreover, since communicating involves conscious action, it is possible to incorporate a wide range of input actions as opposed to automatic detection or absent-minded interactions. We also considered other factors while designing the task, such as asking to design for themself due to limited time for understanding user needs, communication of emotion over distance to make the problem statement relatable and easy to understand, there are only a few TUIs for communicating emotion over distance [81] which ensures lack of familiarity with possible solutions, asking to design for both way communication to balance their focus on input and output, providing a list of emotions to have uniformity while reducing ambiguity, and asking to pick at least three emotions to ease ideating for a variety of input actions.

4.3 Data Collection and Analysis

We used three constructs: tool usage (RQ1), support for conceptualizing TUIs (RQ2), and challenges of using the tool (RQ3). The collected data involved video recordings of the design sessions along with the remote observation notes, deliverables from the participants in the form of written sheets and sketches or models of their ideas, and video recordings of the semi-structured interviews. The first author collaborated with two peer TIxD researchers to analyze the data while co-supervised by the second and third authors.

The interview data was analyzed inductively using open coding, axial coding, and selective coding [15,24,68]. The first author analyzed all twelve interviews (to include all participants) for a first pass, during which her peer researcher individually analyzed three interviews. They then discussed their analysis to arrive at a set of mutually agreed-upon themes. Next, they used these themes to individually analyze one more interview while making any changes to the themes as required. When changes were made to the themes, they revisited the already analyzed interviews for follow-up examinations. This process was repeated until the set of themes required no more changes, which happened after the peer researcher analyzed six interviews. Hence the first author alone analyzed the remaining six interviews using the set of themes they arrived at. She discussed with her peer researcher before making any changes to these themes. In this process, she analyzed the twelve interviews twice, making the analysis more robust. The coders triangulated different data sources, used detailed descriptions, and presented disconfirming evidence, which further contributes to validity.

In deliverable 3, the participants listed the emotions, input actions, and outputs in their final idea. The first author analyzed the deliverable 3 data looking for the types of input actions and outputs in the participants' final ideas while comparing it against 1) input actions and outputs in IdeaBits 2.0 and 2) input actions not in IdeaBits 2.0 that are (not) found commonly in everyday devices and TUIs. In deliverable 4, the participants listed the electronic components required to prototype their final idea. The first author analyzed the deliverable 4 data with a peer researcher for completion, feasibility, errors, and the presence of the listed electronic components in the SEAs. They individually analyzed four participants' data, followed by a discussion of their analysis looking for similarities and differences. Since their analysis was consistent with each other, the first author alone analyzed the remaining eight participants' data.

5 RESULTS

We next describe the themes that emerged from data analysis while using fictional names for the participants. Almost all the findings have been derived from the interview data. For the findings derived from other data sources, we explicitly mention the source. Hence findings with no data source mentioned have been derived from the interview data.

5.1 Hands-on Interaction

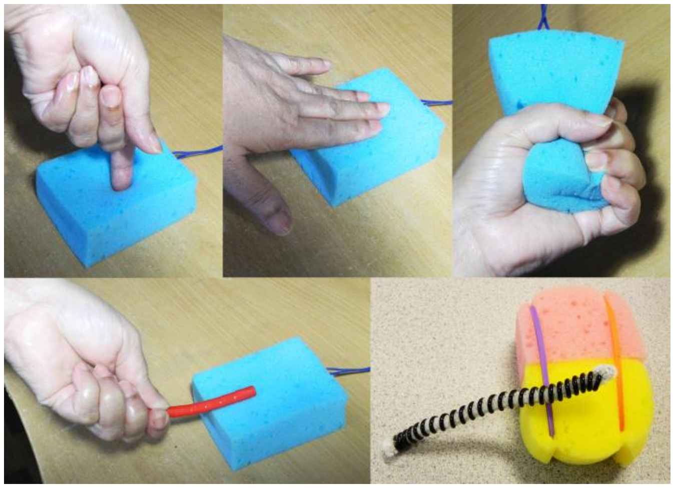

Figure 4: Input action exploration with squeeze SEA – poke (upper left), tap (upper middle), squeeze (upper right), hit (lower left). Ted's TUI idea (lower right) involving hitting the foam block with the stick to communicate 'angry' emotion.

In this theme, we describe how participants interacted with the artifacts and modeling materials and how it helped them get ideas. All the participants interacted with the POAs, SEAs, and modeling materials. Almost all of them stated the reasons behind their exploratory hands-on interactions to be curiosity and to get ideas. For example, some participants said that they interacted with the modeling materials to uncover the input actions the material could afford, which helped them to get ideas. Similarly, investigating aspects of the SEAs (e.g., function, input-output mapping, and technical implementation) were stated by around half of the participants to be the reasons for interacting with the SEAs. Other reasons stated by participants for interacting with the SEAs include – physically feel the SEAs, enact the actions, get ideas, be playful, and test which non-prescribed input actions would be detected. Participants said that, when interacting with the SEAs, getting feedback through their output helped them carry out the explorations and understand the investigated aspects of SEAs. For example, Ted's quote shows that getting output helped participants know when the performed input action was detected. *"I like those [SEAs] just coz I can see at which point does it work… I squeezed it [squeeze SEA] in different ways."* - ***Ted***. This, in turn, helped a few participants explore a variety of input actions and identify which non-prescribed actions would be detected by the SEAs. Such explorations inspired them with input action ideas beyond the ones introduced. Ted said that he tried out various input actions (poke, tap, squeeze) on the squeeze SEA to check which of those would be detected. He also used the bend POA to hit on the squeeze SEA (Figure 4). This inspired him to incorporate 'hit' as an input action in his TUI idea to communicate the 'angry' emotion (Figure 4).

A few participants said that they experimented with the SEAs to figure out their technical implementation, which helped them plan their ideas' technical implementation. Lee's quote shows that having output associated with the SEAs enabled participants to figure out the SEAs' technical implementation through experimental explorations. Lee investigated the fold SEA's technical implementation by connecting its copper tapes (when the artifact was in an unfolded position) using the metallic ruler (provided as a stationery item). When he saw that it triggered an output, he understood the SEA's technical implementation and got an input action idea of wiping a tear (which is a conductor) to communicate the emotion 'sad'. On the other hand, participants said that the absence of output when interacting with POAs made it difficult to imagine possible consequences of the interactions.

*"Using this [metallic] ruler [from provided stationery], I was thinking about ways to do that [connect the copper tapes in the fold SEA]. And then I was thinking, "Hmm, if you are sad [emotion in his idea], there is a tear with salt, which is also a conductor."" – **Lee**.*

Around half of the participants said that interacting with the artifacts helped them experience the associated input actions (Paul's quote), which in turn helped them get ideas involving those input actions and facilitated reflective thinking. For example, as illustrated through Neil's quote, interacting with the artifacts helped a few participants to critically reflect on the introduced input actions, which in turn helped them gain deeper insights such as understanding the differences between some of the input actions they initially considered to be the same.

*"You provided all the sensors here so I can touch and feel and just play with it and see how it works." – **Paul**. "I never really thought about input action this much. It felt like pulling and bending is kind of similar, initially to me, but then it's pretty different." - **Neil**.*

5.1.1 Prototyping and Testing Ideas

In this subtheme, we describe how participants used the artifacts and modeling materials to build prototypes and test their ideas and how it helped them. Most participants said that they got new ideas for input action, outputs, and technical implementation while building (using modeling materials) and interacting with their prototypes. Amy's quote shows that combining modeling materials led to discovering new paired affordances of the materials, which in turn inspired new input action possibilities in her idea. *"I did not thought about sliding [input action] until I put it [bead from modeling material] in [pipe cleaner from modeling material], and then I'm like, "Okay. Now it can slide down."" - **Amy**.*

A few participants also said that they realized issues in their ideas while interacting with their prototypes, which helped them iterate their ideas. Although the SEAs were not designed to enable prototyping, they facilitated participants to test their ideas. For example, a few participants said that they interacted with SEAs to know their input action ideas' technical feasibility. Lee's quote shows that the presence of output and multiple affordances in the stretch SEA enabled him to use it for testing the feasibility of "clench fist" input action idea. *"I was wrapping it [stretch SEA] around my finger and see if I stretched, whether this [detection of clench fist input action idea] happens." - **Lee**.* However, a few participants said that they desired to prototype using the artifacts since they found it challenging to build from scratch using the modeling materials. As illustrated through Ross's quote, some of them even changed input actions in their ideas due to challenges faced in prototyping. *"First, I tried to make something squeezy. So, I tried to make with the playdough [modeling material]. But unfortunately, I couldn't because playdough is too sticky." - **Ross**.*

5.2 Introducing Possibilities

In this theme, we describe how IdeaBits 2.0 introduced possibilities and how it helped the participants. Participants said that IdeaBits 2.0 helped them generate ideas by introducing possibilities in the form of artifacts, modeling materials, TUI examples, and technical implementation guidance. For example, some participants said that it helped to generate ideas quickly by providing inspiration. Some participants said that introducing multiple possibilities helped them understand the introduced concepts and open their minds to multiple alternatives. *"The [TUI example] videos really helped me open my mind because I can see different examples, like what can be implemented." – **Uma**.*

Participants said that IdeaBits 2.0 introduced possibilities related to mainly input actions and technical implementation. **Input action possibilities:** IdeaBits 2.0 introduced five input action possibilities (bend, fold, pull, squeeze, and stretch). A few participants said that since these were not among the ones commonly found in everyday devices, it helped them to get ideas beyond those common input actions (e.g., touch, button press, etc.). *"It [IdeaBits 2.0] suggest me interactions more than like these simple phone interactions like push the button and touch. So that's pretty good."* – ***Ross***. Although the artifacts introduced the input actions, some participants said that since the artifacts were abstract and did not have any real-life application, they were insufficient in demonstrating application possibilities of the introduced input actions, as illustrated through Ted's quote.

> *"I saw this [pull SEA], I interacted with it, but I'm not really sure what it is. But then when I saw those [TUI] video examples, I was like, "Oh, that makes lot more sense." So, a way to quickly show how these very simple things [artifacts] can transfer into full-fledged applications, that did help me a lot."* – ***Ted.***

Hence the SEAs fell short in helping participants to conceptualize their ideas. On the other hand, around half of the participants said that the TUI examples demonstrated real-world usage scenarios of how the introduced input actions can be a part of TUIs, which in turn helped conceptualize their ideas. Some participants also said that TUI examples helped them go beyond how the introduced input actions were incorporated in the artifacts.

Technical implementation possibilities: IdeaBits 2.0 introduced technical implementation possibilities mainly through the "Tech" button by linking to Sparkfun [86] pages. Participants said that they referred to these possibilities to understand the technical implementation of the SEAs, plan technical implementation, and check their ideas' technical feasibility. For example, some participants used the "Tech" button to identify the type of data (analog or digital) involved in the sensors of the SEAs, which they were able to find on the linked Sparkfun [86] pages. Although the "Tech" button helped some participants, almost all the participants faced challenges or were unsuccessful in planning their ideas' technical implementation (more details in the last theme). *"I really like this "Tech" button. It's very useful. It shows the main components you can use and how to use them, and more importantly, what kind of data you are using."* - ***Paul***.

Around half of the participants said that they wanted more examples of input actions and associated artifacts, TUI examples, and technical implementation since those helped them get ideas and do the design task. Some of them also speculated that more possibilities might help them to generate a wider variety of input action ideas and reduce design fixation (more details in the next theme).

5.2.1 Preferences for TUI Example Formats

TUI examples were provided using images, videos, and published papers. Most participants said that they preferred the video format since it efficiently demonstrated the input action, its application, and technical implementation. Also, the colored bars with the video player, which indicated different sections of the video, helped some participants to skim the videos. Some participants, however, said that they preferred the image format as it was faster to view them. None of the participants preferred the paper format while stating reasons such as words being inefficient in describing input actions and reading papers being time-consuming.

> *"With the video, you can see how they are going to do the interaction."* - ***Eva***. *"[I prefer] images, coz even for the video, I was skipping so I can go through it faster."* - ***Kate***. *"You cannot describe how this thing [input action] is gonna be used in words only."* - ***Ross***.

5.3 Examples Causing Design Fixation

In this theme, we describe how IdeaBits 2.0 caused design fixation by inspiring ideas similar to the introduced possibilities, why the participants tried to incorporate the introduced possibilities, and disconfirming pieces of evidence.

5.3.1 Inspiring Ideas Similar to the Introduced Possibilities

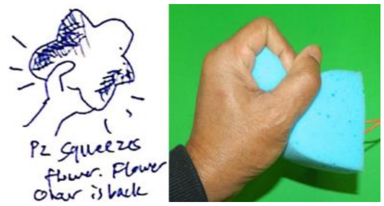

Figure 5: Eva's illustration of squeeze input action in her final idea (left), prescribed way of interacting with the squeeze SEA (right).

In this subtheme, we describe how, at times, the artifacts, TUI examples, and technical implementation information inspired ideas similar to the inspirational source. These similarities occurred concerning input actions, outputs, technical implementation, and overall concept. For example, some participants said that the SEAs inspired their input action ideas. These ideas were, however, the same as those in the artifacts. On top of that, some of the participants who incorporated the introduced input actions did so in a way very similar to the prescribed way of interacting with the artifacts (Figure 5), as found from analysis of the deliverables. Design fixation also occurred when SEAs' technical implementation inspired participants, where the technical implementation plan for the participants' ideas were same as that of the inspiring SEAs; even though some of these ideas involved input actions that were different from those in the artifacts. For example, Lee said that the technical implementation plan of his idea was inspired from and the same as that of the stretch SEA. He, however, used it to detect clench fist input action instead of stretch. Design fixation also occurred when a few participants were inspired by TUI examples they were already aware of and not introduced by IdeaBits 2.0.

5.3.2 Trying to Incorporate from the Introduced Possibilities

In this subtheme, we describe how and why participants tried to incorporate from the introduced possibilities. Almost all the participants said that they tried to incorporate the introduced input action and technical implementation possibilities due to six main reasons. 1) Some participants said that being introduced to a set of possibilities made them focused on those while making it challenging to think of alternatives. Some of them also speculated that such fixation occurred due to being introduced to only a limited number of possibilities. *"Coz, there's only five [introduced] input actions, I think it hinders my imagination to some degree because it makes you focus on what's present. I don't really think of any additional material."* - ***Lee***. 2) A few participants said that the presence of the SEAs in functioning condition, along with associated technical implementation information, gave them confidence in the feasibility of their ideas that involved the introduced input actions. *"I have three ideas, and then I moved on to this one [idea involving fold] just because it [fold SEA] is already there, kind of functioning."* – ***Jane***. 3) When they were not able to get ideas. For example, a few participants said that they tried to incorporate the technical implementation of the SEAs when they were unable to plan technical implementation for their ideas. They even changed the input actions in their ideas to be able to use the technical implementation of the artifacts. 4) To minimize effort. For example, a few participants said that they tried to incorporate the technical implementation of the SEAs to minimize effort, sometimes even when the input actions in their idea were different from those in the artifacts. 5) Due to time shortage. For example, a few participants tried to incorporate the introduced input actions since the 60 minutes duration of the design session was not sufficient to get familiar with the introduced and think beyond them, especially when the introduced possibilities were new to them. *"Since they [introduced input actions] are fairly new to me, it takes me some time to adapt to that before I can think of something else outside the box."* – ***Ross***. 6) Some participants said that they felt expected to incorporate the introduced input actions since they were asked to use the tool during the design session. However, all of them said to have understood the given instruction that they were not constrained to those input actions.

5.3.3 Disconfirming Evidence

In this subtheme, we put forward the other side of the coin by describing some instances where IdeaBits 2.0 inspired ideas without causing design fixation. Some of the participants' ideas were completely different from their inspirational sources, while some others were variations of the introduced possibilities. First, we discuss the analysis of the input actions and output in the participants' final ideas, which provides a mixed picture concerning design fixation. Input actions in the participants' final ideas involved ones commonly found in everyday devices and as well as others, including the ones introduced by IdeaBits 2.0. Eight out of the twelve final ideas involved one or more introduced input actions. However, a total of eight final ideas involved at least one input action that was not introduced by IdeaBits 2.0. Out of these eight ideas, five ideas involved at least one input action which is not commonly found in everyday devices and TUIs (eight input actions in total, such as tear, wipe, twist), while five ideas involved at least one commonly found input action (five input actions in total, such as pressing a button, touch, slide). The participants involved visual, auditory, and tactile output in their final ideas. Eight final ideas involved at least one auditory or visual output, which is the type of output of the SEAs. However, six final ideas involved at least one tactile output.

Based on the interviews, there seem to be three main factors that minimized design fixation. 1) Hands-on interaction helped participants to think beyond the introduced possibilities. For example, a few participants said that interacting with the SEAs helped them to think beyond the TUI examples. Similarly, interacting with the modeling materials helped a few participants get ideas for applying the introduced input actions beyond how they had been implemented in the artifacts, as illustrated through Amy's quote.

> *"That [input action idea of pulling a bead through a pipe cleaner] just popped out while playing with the [modeling] material. And then I thought, "Okay, I was probably thinking in a very limited scenario. It [pull input action] is beyond what it [pull SEA] looks like."" –* ***Amy****.*

2) Ideas were different from the inspirational stimuli when it reminded the participant of another object, activity, or concept. For example, Ted said that the stretch POA reminded him of a telephone cord and how his mother used to wrap it around her finger, which eventually led him to the twist input action idea. 3) Instructions provided to the participants helped minimize design fixation. A few participants said that they did not feel limited to the introduced possibilities and instead saw IdeaBits 2.0 as a source of inspiration, mainly because of the instruction given that they were not constrained to the five introduced input actions.

5.4 Challenges in Using IdeaBits 2.0

Participants faced certain challenges when using IdeaBits 2.0 to do the design task, which were mainly related to the artifacts' output, artifacts' robustness, design guidance, and technical implementation guidance.

Artifacts' output: Having an output associated with the SEAs had many positive impacts (discussed earlier), along with a few challenges. For example, some participants said that they were distracted by popping up of the TUI examples when interacting with the SEAs, not letting them focus on experiencing the input actions. *"I can focus more on the interaction [when interacting with the POAs], instead of having all the videos and images." –* ***Eva***. However, a few participants said that they wanted the SEAs to be the sole controller of the GUI instead of having to keep switching between the mouse and the artifacts. They found it confusing to have two types of controllers, leading to mistakenly reaching out for the SEAs to control parts of the GUI that they knew could be controlled only using the mouse. Also, as found from the analysis of the design session videos, most of the time, the participants were looking at the GUI while interacting with the SEAs presumably as controllers for the GUI.

Artifacts' robustness: Although most of the participants said that they preferred to interact with the SEAs over the POAs, mainly because their output made them interactive and provided feedback, a few participants said that they limited their interaction with the SEAs due to fear of breaking them. They instead chose to interact with the POAs, which they perceived to be robust due to being physical-only. *"Because I know I couldn't break them [POAs], so I played around with them a little bit more." - **Ted**.* The flex sensor in the bend SEA was damaged twice during the study. The flex sensor is supposed to be bent in only one direction, which we indicated by labeling the artifact. Some participants, however, while exploring the artifact, bent it in the prohibited direction, which eventually damaged the sensor.

Design guidance: A few participants said that they expected IdeaBits 2.0 to provide design guidelines related to the input actions, such as how to choose an input action based on context and which input actions go well together.

Technical implementation guidance was mainly provided by linking to Sparkfun [86] pages through the "Tech" button. Although the button helped participants in certain ways (discussed earlier), only one participant listed the technical implementation for input actions correctly (feasible plan with no errors) and completely (all necessary components listed); while around half of the participants said that they faced challenges with the guidance provided. For example, some participants disliked being taken to a web browser when clicking on the "Tech" button and hence suggested incorporating the technical implementation information within the GUI of IdeaBits 2.0. While a few participants said that they did not use the "Tech" button, even though they were unable to plan the technical implementation of their ideas, since they anticipated it to be time-consuming. Participants also perceived the SEAs as technical implementation possibilities. Some participants, however, said that they were not able to understand the SEAs' technical implementation when the involved sensors were not visible, such as the pull and the squeeze artifacts. A few participants also said that they wanted to see the sensors' output values when interacting with the artifacts to be able to understand the involved data type (digital or analog) and inspect their sensitivity. *"I need to see how sensitive the inputs [of the SEAs] are… Like a panel that show you the result of the interaction, right?" – **Ross**.* Another challenge with providing technical implementation information was that a few participants said that it limited their creativity by making them focus on the feasibility of ideas. They speculated that such information might be helpful for later in the idea generation phase when they have narrowed down to a few ideas.

> *"With this [technical implementation information], sometimes you get kind of a reality check of like, "Oh, so this is how you practically build it.", which is really good for a second [idea generation] stage. But in the first one, you kind of need to come up with like gravity machines or whatever." - **Jane**.*

6 DISCUSSION

We now discuss the findings from our study by comparing them with existing literature and provide design recommendations (*in italics*) for tools to support idea generation of TUIs.

6.1 Experiencing Input Actions

In this section, we discuss the benefits of experiencing input actions and how this can be facilitated by providing interactive artifacts. We found that interacting with the artifacts enabled participants to experience the input actions, which in turn helped them notice the similarities and differences between the introduced input actions, think beyond the introduced possibilities, get ideas, and realize shortcomings in their ideas (also found by [32,38,52] for other design domains). Our findings are also consistent with Schon's [64] argument on the importance of "backtalk" from design materials, Gedenryd's [23] emphasis on bodily engagement with design materials during interactive cognition as a critical part of design, and Ingold's [33] insistence on the inseparability of (hands-on) actions from perception in the practice of craft. Hence, *design tools to support idea generation for TUIs need to provide interactive artifacts (that afford physical interactions) to enable experiencing input actions.* Also, *it may help to provide a variety of materials to work with* due to the dependency of TUI design on material properties, as found by [52] for kinetic designers.

Both sets of artifacts facilitated experiencing the input actions by providing passive haptic feedback through the product's physical reaction to the participants' actions. For example, the elongation and reduced flexibility of the stretch artifacts on being stretched provided participants tactile confirmation of their action. Our findings are in line with TUI's aspect of immediate haptic feedback [35] and Djajadiningrat's [17] emphasis on linking action, form, and feedback. Consistent with the concept of double interaction loops in TUIs [35], the SEAs provided an additional (digital) feedback through their output that provided participants confirmation of computational interpretation of their action. This, in turn, helped the participants in many ways, such as encouraging and facilitating hands-on exploration (more details in the following themes). On the other hand, the absence of output when interacting with POAs made it difficult to imagine possible consequences of the interactions. Hence, *the artifacts need to have an output.*

However, some participants found the output of the SEAs (opening the associated TUI example page on the GUI) to be shifting their focus away from the artifact and experiencing the input actions. Designing the SEAs as GUI controllers also resulted in the participants interacting with them absentmindedly while having their primary focus on the GUI. Hence *to facilitate experiencing the input actions, we recommend having subtle and non-intrusive outputs of the artifacts instead of designing them as controllers for the GUI.* Feedback can be provided in a non-intrusive way by say keeping it in the background of the primary task [74], using low intensity [58], or temporally extending it [42]. *To avoid steering users' attention away from the artifacts, we recommend providing the output through the artifact instead of another device.* This is consistent with Wensveen's [79] suggestion to co-locate input and output for being perceived as natural coupling. For example, one can incorporate Djajadiningrat's [17] concept of a 4D form of product reaction, where the output (change in 3D appearance over time) additionally guides how to interact with the object. We did not foresee these issues of the input-output mapping of the SEAs, nor were these discovered during the semi-formal evaluation of IdeaBits.

6.2 Encouraging and Facilitating Hands-on Exploration

In this section, we discuss the advantages of hands-on exploration and how design tools can facilitate it. Encouraging and facilitating exploration of multiple alternatives is beneficial for idea generation, as found by [21,60] as well as from our study. We found that modeling materials and SEAs encouraged and facilitated exploration of input actions. The ambiguity of the modeling materials and interactivity (having output) of the SEAs encouraged exploration by triggering participants' curiosity. Participants interacted with the modeling materials inquiring about their affordances (also found by [69]), leading to exploration of various input actions, which helped them to get input action ideas even beyond the ones introduced in IdeaBits 2.0. We did not provide instruction on how to interact with the modeling materials, which may have encouraged exploration (as found by [38]). Hence, *to encourage exploration, we recommend providing unfamiliar and ambiguous artifacts with open-ended interaction possibilities while not being prescriptive about the associated input actions.* The SEAs encouraged exploration, despite being associated with prescribed input actions, by triggering participants' curiosity to find out how they work and test their sensitivity (also found by [67]). Such explorations helped participants to generate ideas for input actions involving variations of the introduced input actions and input actions not introduced by IdeaBits 2.0 (also found by [52]). Hence, *to encourage exploration, we recommend providing interactive* *(having output) artifacts. For an added objective of discovery, one may link the artifacts with unexpected outputs*, similar to the Blue Studio [38], which may also help users to change their perspectives and get new ideas as found by [38].

To facilitate exploration, we recommend providing artifacts with output and flexible affordances. Explorative interaction with the SEAs was facilitated by feedback (from its output) and versatility in their affordance. For example, the squeeze artifacts (Figure 2), made from a foam cube, afforded to tap and poke, along with squeeze. Despite such versatility, the artifacts' designed affordances to a large degree determined the ways that participants interacted with those. Our findings are in line with the notion of designed affordances in which the physical aspects of an object impact the opportunities for interaction by enabling some actions but not others and by driving users' perception of how to interact with it [43]. For example, the bend artifacts (Figure 2), made using glue gun stick, afforded to bend but not twist. *To facilitate open-ended explorations of a wide range of possibilities, we recommend introducing versatility in the artifacts' designed affordances by carefully considering various physical aspects (e.g., material, form, size). Further, these aspects may be changed over time (as discussed in [17]). We also recommend minimizing the possibilities of technical malfunctioning along with making the artifacts visibly robust to encourage playful, explorative, and worry-free interactions.* We found that some participants, while exploring the bend SEA, bent it in the prohibited direction, which eventually damaged the flex sensor. At the same time, some participants limited their interaction with the SEAs due to fear of breaking them.

6.3 Facilitating Prototyping

In this section, we discuss the advantages of prototyping for TUI designers and how design tools can facilitate it. We found that building (using modeling materials) and interacting with prototypes (electronically non-functional) helped participants get ideas, make design decisions, and realize issues in their ideas. Our findings are in line with [11,52,63]. For example, [52] found that when designing actuated products, iterative prototyping helped designers make successful design decisions due to the high dependency of kinetic design on materiality. Although the SEAs were not designed to enable prototyping, some participants wanted to use them for prototyping to avoid reinventing the wheel by building from scratch. *The SEAs can be provided as pluggable modules that can be used to quickly build, interacting with, and modify functional prototypes with low implementation burden.* Other researchers have found that reducing implementation burden enables designers, especially novices, to focus on the design of the interaction [63] and encourage exploration of ideas [52,63]. They also found that modular plug-and-play tools facilitate exploration during electronic prototyping [2,62,63], however, at the cost of reduced flexibility and modifiability [53,63].

6.4 Inspirational Examples Versus Design Fixation

In this section, we discuss the benefits of providing inspirational stimuli, the possibility of inspirational stimuli causing design fixation, and some strategies to minimize design fixation. Our study and many other researchers (e.g. [14,38,67]) have found inspirational stimuli to be beneficial during idea generation. We found that TUI examples, artifacts, and modeling materials acted as inspirational stimuli and helped participants to get ideas. Some participants were not even able to get any ideas before they started using IdeaBits 2.0. Hence, *we recommend providing examples for various aspects of TUIs, such as input action and output, in the form of interactive artifacts and digital examples of TUIs.*

Inspirational stimuli may, however, also lead to design fixation, as found in our study and by many other researchers (e.g. [40,59,71]). We found that participants, at times, blindly adhered to certain concepts, aspects, or elements of the inspirational stimuli, leading to the generation of ideas that are similar to the stimuli. Design fixation occurred mainly due to four reasons. 1) **Virtue of presenting** – The mere virtue of presenting the tool to the participants made them inclined to incorporate the introduced possibilities in their ideas. It directed their focus towards the presented set of possibilities while making it challenging to think beyond those (also found by [54,55]). 2) **Limited number** – Introducing a limited number of possibilities for input actions and output of SEAs led to design fixation (also found by [48], differed by [16,56]). 3) **Format** –Examples' format played a role in design fixation (also found by [7,13]). For example, providing the input action examples in a technically functional format (SEAs) skewed participants' perception of feasibility to be higher for the introduced actions compared to other possibilities. 4) **Minimizing effort** –Choosing options from the provided repository of possibilities was perceived by participants to be quicker and easier than coming up with new ideas. Hence they opted for the 'path-of-least-resistance' (also found by [77,78]).

We also identified four key factors that helped reduce design fixation. A) **Hands-on exploration** - Enabling hands-on exploration helped go beyond the introduced examples by facilitating reflective thinking and discovery of new possibilities. B) **Introducing variety** –Using multiple formats (POAs, SEAs, TUI examples) introduced variations of the input actions and reduced design fixation. Other researchers have found that diversity in stimuli increases ideas' originality [26]. C) **Novel examples** – Providing novel examples of input actions, which are not found in everyday devices, helped participants to overcome their fixation on such common input actions (also found by [56]). D) **Mixing possibilities** – Providing TUI examples from outside the given design task's solution set helped reduce design fixation by avoiding generation of ideas that were replicas of a single example (also found by [16], differed by [25,71]). It led participants to mix and match different components (e.g., input, output, technical implementation) from different examples and add their creations while synthesizing these into TUI ideas.

Based on the above, *to minimize design fixation, we recommend - 1) providing a large number of novel examples while including variety and avoiding the solution set, 2) facilitating hands-on exploration of the introduced possibilities, and 3) encouraging users to combine possibilities to discover new ones; e.g., combining materials to discover new affordances.*

6.5 Technical Implementation Guidance

In this section, we give guidelines on how to provide technical implementation guidance. IdeaBits 2.0 provided technical implementation guidance through the "Tech" button and the SEAs. We found that although the provided guidance helped in certain ways, almost all the participants were unsuccessful in planning the technical implementation of their input action ideas. The issue with the "Tech" button was with its delivery of the information rather than with the content. For understanding a sensor, participants wanted to know the involved data type, sensitivity, and how to use them (also found by [63]); which they mentioned was provided through the "Tech" button. However, some participants did not use the "Tech" button as they anticipated it to be time-consuming. Being taken to a web browser might be one of its reasons, which in fact, some participants said that they disliked. Hence, *we recommend providing technical implementation information (including the sensors' data type, sensitivity, and how to use them) within the GUI,* as also suggested by some participants. *Doing so will provide easy and quick access to the information while enabling to design the information organization, presentation, and delivery formats in a way that facilitates quick comprehension.*

Technical implementation possibilities introduced through the SEAs had issues in terms of not being able to see the involved electronics (also found by [89]) and the output values of the sensors. Hence, w*e recommend designing the artifacts in a way that users can easily open them up to access the involved electronic components at their will, along with displaying the sensors' output values. However, we do not recommend designing the artifacts in a way that the involved electronic components are revealed upfront* since introducing technical implementation details may reduce creative confidence as found in our study and by [62]. Similarly, *other technical implementation information can also be provided such that it is displayed only when the user makes an active choice to access it.* Technical implementation possibilities introduced through the SEAs also presented certain benefits. For example, physically interacting and experimenting with the SEAs, while getting feedback from the output, helped participants to uncover the fundamental concepts of the involved electronic components; which in turn helped them to use these concepts for detecting different variations of the introduced input actions, as well as for detecting input actions beyond the ones introduced (also found by [52]). Hence, *we recommend introducing technical implementation possibilities in the form of interactive artifacts. Additionally, showing the SEAs' output and input data values*, as also suggested by some participants, *and enabling to tweak their sensitivity, may further facilitate exploration and understanding of the artifacts' technical implementation. Such information can be shown when a user plugs in the artifact to say a technical inquiry platform.*

6.6 Value of IdeaBits 2.0

In this section, we discuss how the different components and aspects of IdeaBits 2.0 contributed to its value. Participants used the artifacts to generate ideas by carrying out hands-on exploration, investigating their properties, examining possibilities beyond the introduced, enacting physical actions, and testing ideas. These activities helped them get ideas by experiencing the input actions, critically reflecting on the introduced actions, understanding the artifacts' investigated aspects, discovering unexpected possibilities, and realizing issues in their ideas.

The artifacts helped participants to experience input actions by providing them with a physical medium to carry out the actions. In the absence of such a facilitative medium, one would have to perform the actions as gestures in the air while imagining what it would be like to interact with a physical interface affording that action. Even though each artifact was associated with a specific prescribed input action, their flexible physical affordance facilitated open-ended hands-on explorations of various physical interactions, including those beyond the prescribed ones. For example, participants utilized the stretch POA's and squeeze SEA's affordance for twist and poke, respectively. When an artifact was perceived to be robust, it encouraged participants to carry out carefree hands-on explorations.

The difference between the two types of artifacts (SEAs and POAs) is that the SEAs have output. Hence interacting with the SEAs enabled participants to experience their input-output mapping, where they saw an example of what the output of the performed input action could possibly be. On the other hand, when interacting with the POAs, participants had to imagine output possibilities. They found this challenging. Having output associated with the SEAs attracted participants to interact with them and encouraged exploration by triggering curiosity. Having output also facilitated such hands-on explorations by providing feedback. For example, getting output helped participants know when the performed input action was detected, which helped them explore input actions beyond the ones prescribed.

The artifacts are extractions of building blocks of TUIs – input and output. Both POAs and SEAs are extractions of input, involving simplified and generic implementation of a set of input actions. Although the SEAs involve both input and output, these are abstract artifacts with no recognizable real-world usage. On the other hand, the TUI examples demonstrated how the introduced input actions can be incorporated as a part of TUIs through real-world usage scenarios. Providing such examples helped participants to develop an understanding of the bigger picture, which in turn helped them conceptualize their ideas. Hence, simplifying the learning task through extractions of the building blocks helped reduce intrinsic cognitive load, and subsequent additions of the omitted elements through the different components of IdeaBits 2.0 helped commence understanding (also suggested by [50]). However, such extraction of input action is not to be mistaken with assumptions such as input can be combined with output independently, or they always are provided through different devices. In TUIs, input actions are afforded by the physical artifacts, which are also (tangible) representation of digital information [73]. For designing successful TUIs, [35] emphasizes the importance of a balanced and tight perceptual coupling between the tangible representation and the output. [79] emphasizes the importance of coupling input and output in TUIs and provides six practical characteristics for the same. This interdependency of input, tangible representation of digital information, and output must be carefully considered when designing TUIs.

7 CONCLUSION

Our work makes three main contributions. 1) We contribute an improved version of IdeaBits [9] as a tool to aid idea generation for TUI input actions. We open-sourced the code [72] to enable other designers and researchers to use it for creating similar prototypes. It would provide some standards and starting points for other designers designing similar tools. 2) The results from the evaluation of IdeaBits 2.0 provide a foundation for other researchers to build upon while conducting further research on this topic. We also provided various study materials (e.g., questionnaires, participants' deliverables) in appendices and as supplementary material to facilitate further research. 3) We provided a set of design recommendations for tools to support novice TIxD students in generating input action ideas, which designers can use as guidelines while designing such tools. The recommendations can also be explored for their generalizability to other user groups (e.g., TUI designers, senior TIxD students), other similar domains that involve embodied interaction or designing physical products (such as gestural interfaces or product design), and creative activities in general.

While our work presents promising opportunities, it has certain limitations. We conducted a semi-formal evaluation of IdeaBits [9] to design IdeaBits 2.0. For example, the first author, who is not an expert in TIxD, did the heuristic evaluation. Conducting it with three to five experts may help to identify around 80% of the usability problems [1,45]. We are aware of four limitations of the user study we conducted. First, it was conducted in an experimental setup while being videotaped and remotely observed, which may have influenced participants' task performance and interaction with IdeaBits 2.0. The study involved the users completing the design task individually. Users may use IdeaBits 2.0 in a different way when they work in groups. The design session being only one hour-long, the participants had limited time to interact with IdeaBits 2.0, that too as first-time users, while also being asked to perform a specific unfamiliar design task. They may use IdeaBits 2.0 differently over an extended period of time and when working on a different task, e.g., a graded TIxD course project. Second, absence of a control group makes it challenging to know the effectiveness of the tool. Third, participants were selected from limited demographics, involving students from only SIAT. Therefore, the department's specific education and culture might have influenced the findings. Considering additional factors (e.g., competency in TIxD, expertise in electronics etc.) in screening and segregating the participants may enhance the findings. Fourth, a part of the data was analyzed by only the first author, who also designed the tool, conducted the interviews, and did the remote observation. Hence there may be bias in the conclusions drawn from the study.

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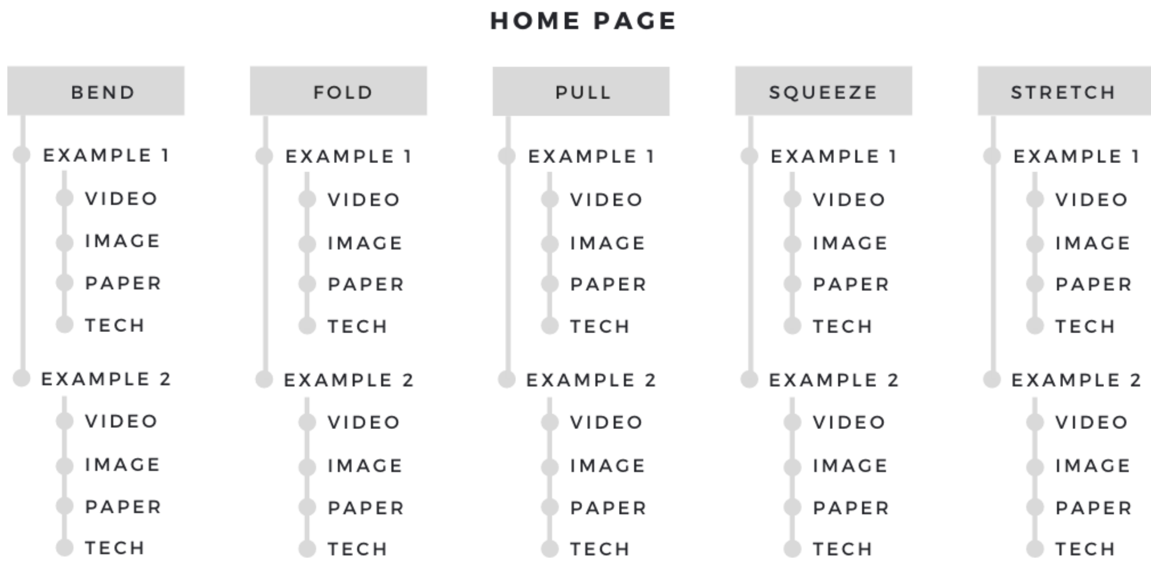
A APPENDICES

A.1 GUI of IdeaBits 2.0



Sitemap diagram.

Home page.

Video format of TUI examples. The TUI example shown is Memento [47].

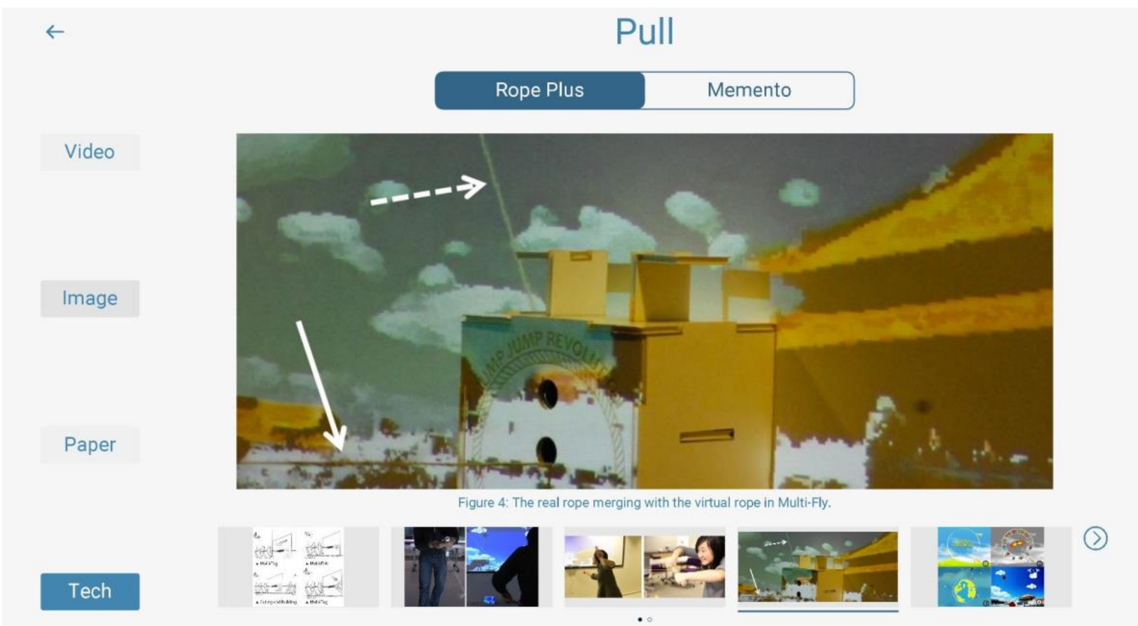
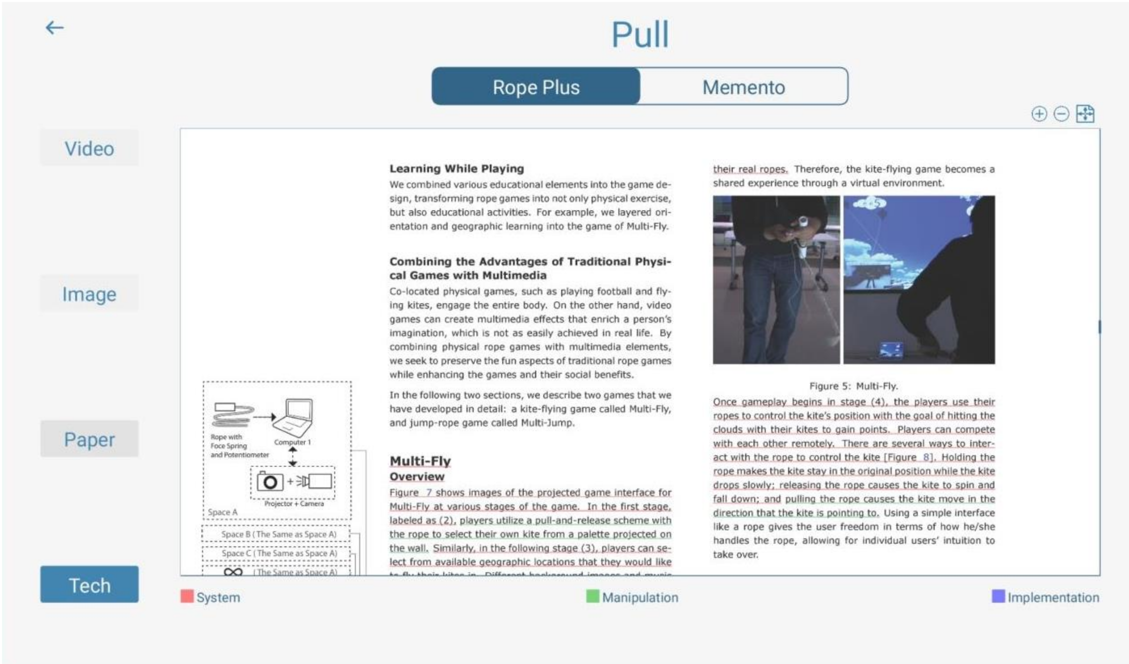


Image format of TUI examples. The TUI example shown is RopePlus [82].



Paper format of TUI examples. The TUI example shown is RopePlus [82].

A.2 Screening Questionnaire

1. **Name:** What is your official name?

   ____

2. **Gender:** To which gender do you most identify?

   ☐ a. Male

   ☐ b. Female

   ☐ c. Other

3. **English fluency:** How would you describe your ability to communicate about your design ideas in English?

☐	☐	☐	☐	☐
1	2	3	4	5
Poor	Bad	Fine	Good	Excellent

4. **Physical disability:** Do you identify yourself as someone with physical disability?

   ☐ a. Yes

   ☐ b. No

5. **Cognitive disability:** Do you identify yourself as someone with cognitive disability?

   ☐ a. Yes

   ☐ b. No

6. **Tangible interaction design experience:** How would you rate your experience with designing tangible user interfaces?
   Tangible user interfaces involve use of physical objects to interact with digital content.

☐	☐	☐	☐	☐
1	2	3	4	5
No experience	Beginner	Intermediate	Advanced	Expert

7. **Tangible interaction design education:** Have you taken any of the following courses? *Mention **when you took the course**.*

- ☐ a. IAT 106 - Spatial Thinking and Communicating ______________________
- ☐ b. IAT 233 - Spatial Design ______________________
- ☐ c. IAT 320 - Body Interface ______________________
- ☐ d. IAT 333 - Interaction Design Methods ______________________
- ☐ e. IAT 351 - Advanced Human-Computer Interaction ______________________
- ☐ f. IAT 438 - Interactive Objects and Environments ______________________
- ☐ g. IAT 832 - Exploring Interactivity ______________________
- ☐ h. IAT 882 - Special Topics II ______________________
- ☐ i. Any other Special Topics IAT course(s)? *Mention **name**(s) and **when** you took it.*

  ____

- ☐ j. Any other Tangible interaction design course(s)? *Can be courses taken outside of SIAT or even online. Mention **name**(s) and **when** you took it.*

  ____

8. **Tangible interaction design:** Please briefly mention your prior experience (as a student, researcher, employee etc.) with tangible interaction design.

____

____

____

____

9. **Additional comments** *if any*:

____

____

____

____

A.3 List of Stationery and Modelling Materials

Stationery

1. A4 Papers
2. Clip board
3. Color pencils
4. Erasers
5. Geometry box
6. Pencils
7. Pens
8. Rulers
9. Sharpeners
10. Sketch pens
11. Sketching papers
12. Stapler and pins
13. Sticky notes
14. Whiteners

Modelling Materials

1. Beads
2. Bendable sticks
3. Both sided tape
4. Cello tape
5. Chart papers
6. Clothe pieces
7. Construction paper
8. Craft board
9. Cubes
10. Cutters
11. Cutting board
12. Elastic
13. Elastic sheet
14. Felt sheets
15. Foam shapes
16. Glue
17. Glue gun, sticks, pad
18. Ice-cream sticks
19. Jute rope
20. Ladder cable ties
21. Legos
22. Magnets
23. Masking tape
24. Measuring tape
25. Modeling clay
26. Needle and thread
27. Packing tape
28. Parachute cord
29. Permanent markers
30. Pipe cleaners
31. Playdough
32. Pom poms
33. Reusable adhesive
34. Ribbons
35. Rings (wooden)
36. Rubber bands
37. Safety pins
38. Scissors
39. Sponge cubes
40. Spring
41. Sticks
42. Straws
43. Suction cups
44. Super glue
45. Thread and needles
46. Toothpicks
47. Twist ties
48. Velcro straps

A.4 Interview Questionnaire

1. Congratulations on completing the session. How did it go?
2. I am curious about the ideas you came up with. Can you help me understand your final idea (referring to the deliverables in sequence)?
3. Can you walk me through your process of how you came up with this final idea?
   a. (If they did not explore multiple ideas) How many ideas did you explore? Why so?

4. What are the ways you used IdeaBits 2.0 to do this design task?
5. Do you prefer either the POAs or the SEAs? Why so?
6. Do you prefer the image, video or paper format for the examples? Why so?

7. Let us discuss further the input actions you explored. Can you walk me through how you came up with these input actions in your final idea?
   a. (If not already mentioned) Did you use IdeaBits 2.0 to come up with input action ideas?
      a. (If they used IdeaBits 2.0) How did you use it?
      b. (If they did not use IdeaBits 2.0) Why did you choose not to use it?
   b. Did you face any challenges while generating IA ideas? (If they faced challenges) What challenges did you face?
8. Did you come across any input actions you were not familiar with?
   a. (If they came across any unfamiliar input actions) Which input actions you were not familiar with? Could you explore any of these in your ideas?
      a. (If they explored) Can you tell me which ones did you explore? Can you tell me how you explored them?
      b. (If they did not explore) Why not?

9. Can you tell me what you did for planning technical implementation?
   a. (If not already mentioned) Did you use IdeaBits 2.0 for planning technical implementation?
      b. (If they used IdeaBits 2.0) How did you use it?
      c. (If they did not use IdeaBits 2.0) Why did you choose not to use it?

10. In what ways, if any, do you think IdeaBits 2.0 helped you in doing the design task?
11. In what ways, if any, do you think IdeaBits 2.0 hindered or limited you in doing the design task?
12. Can you tell me about the challenges you faced, if any, while doing the design task?
13. Can you tell me about the challenges you faced, if any, while using IdeaBits 2.0? (If they hesitate to mention negative things) IdeaBits 2.0 is in a very rough prototype phase. We would be more than happy to know ways in which we can improve it. So please feel free to mention anything you did not like.
14. The goal of IdeaBits 2.0 is to help you generate ideas for input actions. If we were to revise IdeaBits 2.0, what changes would you like to see? Why so?
15. To wrap it up, the goal of this study is to understand how you use IdeaBits 2.0 to generate ideas for input actions. What else you would like to mention to help us understand your experience better?
    a. Is there anything else you would like to discuss?

A.5 Design Task

Tangible system for emotion communication over distance

Generate ideas for a tangible system, involving one or more physical objects, which you can use to communicate how you are feeling to a partner/friend/family member over distance. The system should enable him/her to receive the feeling you communicate as well as communicate back theirs. It should also enable you to receive the feeling he/she communicates to you.

1. **What**: A **tangible system** involving **one or more physical objects**
2. **Users**: You and a partner/friend/family member who lives far away
3. **Goal:**

   a. You can **communicate how you are feeling** to your partner
   b. Your partner **receives the feeling you communicate**
   c. Your partner can **communicate how they are feeling** to you
   d. You can **receive the feeling your partner communicates**

Constraints check list

☐ 1. Pick **at least three** emotions from:
Happy Sad Scared Angry Disgusted Surprised

☐ 2. Think **beyond** emoticons.

☐ 3. You may **use any type of input action**. You are **NOT** limited to the ones in Idea Bits.

☐ 4. Generate **multiple ideas** and from there select **1 final idea**.

Deliverables

Please attach extra sheets as needed.

1 of 4. What does the conceptual design of **your idea look like**? *You may* **sketch** and/or make a **rough physical model** (**without** electronic components)

Description: (Optional)

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2 of 4. How does the conceptual design **support communication of emotions** over distance?

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3 of 4. Describe all the **input actions** a user can perform on the tangible objects in the conceptual design? How does the **conceptual design respond** to each of the above input actions from the user? What is the **emotion** being communicated?

*You may use any type of input action. You are **NOT** limited to the ones in Idea Bits.*

Emotion(s)	Input action	Response/output

4 of 4. List the **electrical components** you will need to build a low fidelity prototype of the conceptual design? *For example, which sensor(s), if any, you will need to detect the input action(s).*

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