Transcribing Across the Senses: Community Efforts to Create 3D Printable Accessible Tactile Pictures for Young Children with Visual Impairments

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ABSTRACT

The design of 3D printable accessible tactile pictures (3DP-ATPs) for young children with visual impairments has the potential to greatly increase the supply of tactile materials that can be used to support emergent literacy skill development. Many caregivers and stakeholders invested in supporting young children with visual impairments have shown interest in using 3D printing to make accessible tactile materials. Unfortunately, the task of designing and producing 3DP-ATPs is far more complex than simply learning to use personal fabrication tools. This paper presents formative research conducted to investigate how six caregiver stakeholder-groups, with diverse skillsets and domain interests, attempt to create purposeful 3DP-ATPs with amateur-focused 3D modeling programs. We expose the experiences of these stakeholder groups as they attempt to design 3DP-ATG for the first time. We discuss how the participant groups practically and conceptually approach the task and focus their design work. Each group demonstrated different combinations of skillsets. In turn, we identify the common activities required of the design task as well how different participants are well suited and motivated to preform those activities. This study suggests that the emerging community of amateur 3DP-ATP designers may benefit from an online creativity support tool to help offset the challenges of designing purposeful 3DP-ATPs that are designed to meet individual children with VI's emergent literacy needs.

Categories and Subject Descriptors

K.4.2 [Computers and Society]: Social Issues– assistive technologies for persons with disabilities.

General Terms

Design; Experimentation; Human Factors

Keywords

Visual impairment; emergent literacy; tactile pictures; tactile graphics; accessibility; 3D print; 3D model

1. INTRODUCTION

Emergent literacy is the process in which a young child constructs concepts about the function of symbols and print. It is based on experiences and meaningful language facilitated by interactions with adults. For sighted children, pictures and illustrations provide a bridge between listening and early reading behaviors. These visual stimulants play a major role in enriching the storyline and adding humor and intrigue, giving instant clues that enable the reader to reconstruct the story. Children only gradually become aware of the text over time; it is the illustrations that help a child recall the meaning and words of a story [30].

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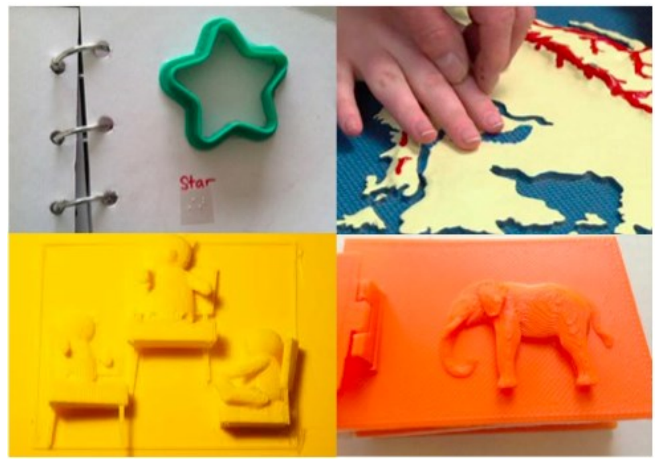

Figure 1. Top: Handcrafted 2.5D-ATP/ATG (Source: Perkins School); Bottom 3D Printed 3DP-ATP (Source: Ref. 19, 39).

Children with visual impairments (VI) often miss the opportunity to learn from illustrated children's books because their perception is limited to what can be felt by the hand, seen within a limited visual field, and heard. Children with VI often have difficulty understanding the gestalt, or whole nature of an experience [16]. Accessible tactile pictures (ATPs) consist of tactile representations that convey different kinds of messages and present information through the sense of touch to further a child's cognitive-affective and relational development [14]. Successful ATPs for young learners (kindergarten through 3rd grade) focus on representing content in a tactile manner that builds a younger child's understanding of symbolic representation and confidence to explore their environments and make associations through the sense of touch (tactile acuity). They can be used during co-reading experiences between a caregiver and a child, and help convey relationships, concepts, and story objects relevant to the child's learning. Reading and play with ATPs an important role in developing emergent literacy skills in young children with VI because they support joint attention with a child reads with caregivers [38], offer children with a means to be an active participant in the reading experience, and offer opportunities for interaction with their peers. ATPs and ATGs are most successfully used along side other verbal description of the story.

The Braille Authority of North America (BANA) indicates that solid shapes are more easily recognized than outline of shapes and objects for young readers, who are learning emergent literacy skills [10]. If designed well, ATPs can support one's learning from part to whole, and help prepare children with VI to make a stress-free transition to accessible tactile graphics (ATGs), which blind learners are likely to use as they advance in their education [14]. ATGs focus on conveying science, technology, engineering, and math (STEM) topics, which are commonly transformed representations of diagrams, charts, maps, and drawings.

The design of ATPs and other accessible materials, like the design of many assistive technologies (AT) [20], greatly benefits from the consultation and involvement of end-users and their caregivers. Of late, many caregivers and other stakeholders of children with VI have identified the opportunity of 3D printers to make low-cost, highly customized tactile forms, objects, and books containing 3D printed accessible tactile graphics (3DP-ATGs) and 3D printed accessible tactile pictures or illustrations (3DP-ATPs) [36] (Figure 1). Unlike traditional ATG and ATP production methods (embossers, thermoform, handcraft) 3D printing allows for the rapid production of solid forms and personalized ATPs. However, despite the growing popularity of 3D printers and their affordances, the complexity of the design task creates a barrier to using 3D printers for creating ATPs.

In this paper, we present formative research to identify how caregivers and stakeholders of people with VI engage in the design practice of making accessible 3DP-ATPs and how they innately approach 3D modeling, tactile graphicacy, decoding, and other skillsets to achieve the design task. Through conducting six workshops, with 67 participants in total, we observed the workshop groups' abilities, and conceptual and practical approaches to transcribing visual pictures into meaningful 3D tactile experiences.

While no one participant group fully accomplished the design task during the workshops, we noted a clear division in the groups' approaches, and thus propose how different stakeholder groups' abilities can be leveraged to accomplish the multidisciplinary design task. We expand upon the previous work on assessable tactile and sound-based materials for people with VI, and 3D printed assistive technologies (AT). This research also contributes to an ongoing effort to design and develop an online digital library and creative collaboration tool that bridges the social and design capital those committed to supporting emergent literacy.

2. BACKGROUND

ATG and ATP Production and Supply: Organizations serving blind communities have been making children's books for VI children for years. In the United States, publishers e.g., American Printing House for the Blind (APH) and National Braille Press (NBP), and tactile graphic artists have been the primary producers of ATGs and ATPs. NBP carries a catalog of 100+ children's books [32] and Seedlings, a nonprofit organization dedicated to providing low-cost Braille books for VI children, has a catalog of 1,200 titles [35]. In addition to the mass produced books, several organizations in the United States and Europe have organized ATG and ATP book competitions in order to entice artists and other stakeholders to create new material [5].

However, the supply of these books is limited due to the time and cost involved with designing and validating the content, creating the thermoform and other subtractive molds, and subsequently producing the material in bulk. Many of the books that are produced are oriented to older children, and do not contain purposeful representations for those who have not yet learned Braille or more advanced decoding skills. Furthermore, much of the material is not easily customized to meet the unique learning needs of an individual child. In turn, when purchasing traditional ATPs and books from publishers or artists, caregivers often face a tradeoff between cost, supply/selection, and appropriateness for their child's unique needs.

Need for Individualized ATPs: Many teachers of the visually impaired (TVIs) advocate that ATPs should be designed for the individual, specifically focusing on creating material that focuses on specific skill development and the knowledge needed to comprehend them [3]. The ways in which people learn tactile and haptic perception and acuity is greatly varied, and is dependent on their cognitive abilities as well as their learning environments. The caregivers (parents, TVIs, etc.) and artists who choose to take the time to manually make ATGs and ATPs for individual children have traditionally used a wide variety of textured materials, including textured fabric, paper, foam paper, and the like. These ATPs are often fragile and are not easily reproduced.

Of important note, the development of emergent literacy skills four young children with VI is not solely dependent on the use of ATPs. Students need assistance in interpreting the information being presented in ATPs [10] Best educational practices include additional activities to help individual children match pictures to sounds, letters, words, and the environment around them. A variety of touch graphic technologies providing non visual feedback, including but not limited to, The Talking Touch Tablet [27], Talking Tactile Pen [28], QR Codes to Access [9], that have been developed to embed various interfaces with auditory information that help individuals interpret information.

ATG and ATP Design Guidelines: For those who focus on designing ATP for bulk production or individual users, alike, there are resources available to guide their design work. The BANA guideline, provide ATG designers and braille transcriptionists with best practices and conventions for raised line/ 2.5D tactile representations, including: consider the cognitive obstacles to peoples' successful use of ATG and ATP; touch cannot discriminate the fine detail that sight can; extract information through a sequence of touches and then re-integrating it imposes a heavy memory load; assure that conceptual graphical representations are augmented with interpretation [10]. Like visual picture illustration, however, there is no single approach to designing ATGs and ATPs, and the guidelines will only go so far to inform one's design process. To the best of our knowledge, no formal work has been conducted to evaluate how or if caregivers and other stakeholders design ATPs according to the recently published guidelines, or whether the existing 2.5D guidelines are applicable to the design of 3DP materials.

Albeit, many TVIs, artists and other designers of ATG agree that when transcribing a graphic illustration into an ATG and ATP, graphicacy aids one's ability to create meaningful materials. Graphicacy depends on one's ability to decode graphic elements [4]. Aldrich suggests activities for teaching tactile graphicacy should include refining the scope of graphic formats being taught, strategically selecting contextual examples of graphics, presenting multiple versions of graphics representing similar concepts, prompting students to think of the merits of different formats, and providing opportunities for students to gain their own hands on experience with designing [2]. To this point, BANA states, "the best method for learning how to prepare a tactile graphic comes from hands on training, from critical feedback from other tactile producers and tactile graphics readers, and from experience [10]."

3. RELATED WORK

3D Printing ATG: Recent work has focused on the feasibility of using 3D printers to create AT and tactile materials [11, 25] however, many of these efforts only concentrate on the material feasibility of 3D printing STEM-focused tactile graphics or the interest of the community in using the technology, as opposed to issues of accessibility [39]. Discussions about the limitations of 3D printers for the production of tactile graphics and pictures due to the resolution of the prints highlight some potential limitations of the technology. However, recent advances in the technology are eliminating these concerns. Hudson shows that 3D printers are not limited to printing plastic [21].

AT Requirements: Several efforts have focused on the feasibility and requirements for using 3D printing in context of serving populations with varying ability, including individuals with cognitive, motor, and visual impairments. Buehler, et al. explored how 3D printing can address the concerns of designing AT and customized solutions for young students in special education environments [11]. They identified requirements for making 3D printers accessible to learners and caregivers in such environments, including: make accessible software, consider the learning curve, encourage sharing of existing models, and support editing existing models. McDonald, et al. discussed how digital fabrication can support the creation of educational aids for providing accessible curriculum content [31].

While these efforts provide great insight into the requirements for using 3D printers in special educational contexts, they do not discuss the range of stakeholders involved in approaching a specific AT educational design task with 3D printers. Hook et al. conducted interviews with 11 caregivers to explore the challenges that are, or might be, faced by non-professionals when making DIY-AT (generally) and the challenges of making DIY-AT for children with disabilities [20]. This research revealed the community's value of rapid prototyping technologies and the need for the creation of practical communities to help lower the barrier of entry for caregivers with little technical experience. They recommend an increase in practical services and communities that support and encourage larger numbers of non-professionals to become involved in making and adapting AT. To this point, Buehler, et al. presents a systematic evaluation of assistive technology creation and dissemination in an online community of assistive technology makers on Thingiverse [12]. They found that many of the shared DIY assistive technologies are created by people with disabilities or on behalf of friends and loved ones, and that these designers frequently have no formal training or expertise in the creation of assistive technology. Their findings did not include information related to the activities people engage in in order to design materials for children with VI, but they do call for efforts to engage people in the design of AT.

DIY AT Design Tools: A variety of efforts have been taken to design digital tools to support caregivers, stakeholders and people with disabilities designing AT [15, 22]. However, we have not found any project that supports users in creating 3D printable 3DP-ATPs for young children. In recent years, there has been a rise in the development of 3D digital fabrication tools for education and amateur users in order to lower the entry point to learning 3D modeling, in general. SketchUp [41], Tinkercad [8], and 123Design [6] have been designed to lower the threshold of learning for novice users while providing professionals a high ceiling for use. Unlike traditional 3D modeling programs (Rhino [34], SolidWorks [37], Maya [7]), amateur-focused tools tend to hide the underlying geometrical figures, algorithms, and vectors of the objects. Lastly, the CHI and IDC communities have focused on developing constructivist learning through 3D modeling with alternative inputs, including the UCube [29], KidCad [17], and FabCode [1]. Zeising et al. propose a series of criteria for a new wave of constructivist-based digital fabrication (modeling) software design, which, if applied, may continue to reduce the barriers of entry into 3D modeling [43]. All of these efforts have yet to build in support features for designing ATG/3DP-ATP.

4. RESEARCH METHOD

Our key research questions regarding the design of 3DP-ATP for children with VI are: (1) *What distinct stakeholder groups are interested and willing to contribute to developing 3DP-ATP, and how/what do they contribute;* (2) *How do these groups differ and what do they have in common in terms of motivation, design approach, and skill*; (3) *How can distinct stakeholder groups' skills be leveraged to increase the supply of 3DP-ATP?*

4.1 Stakeholder Groups

Background: Prior to this work, our team designed and 3D printed a series of 3DP-ATP prototypes. Through word-of-mouth and news media coverage, we received a large number of email requests from various people for samples. We subsequently delivered samples to meet a subset of these requests, limited to those who self-identified as parents or teachers of VI children because they were our priorities [39]. Informally, we were told by many of the recipients that, if possible, they would like to learn and be able to design and make 3DP-ATPs on their own. A majority of the requests came from parents or TVIs. However, we also received a significant number of email inquires from other sorts of people not traditionally associated with the blind community. Many expressed a strong desire to help design and make 3DP-ATPs. Prior to this work, we had not yet made a systematic attempt to understand who they were, what they might be able to contribute, and how their knowledge or skills may complement those of the parents and TVIs. We intentionally decided to exclude parents from this research due to another concurrent study focusing on how parents approach the design of ATG and other AT.

Participant Selection: First, we revisited all of the email requests we received, paying specific attention to those coming from people other than parents, TVIs, or blind people. We clustered the emails based on the job titles of the senders. In many cases, the sender would self-identify his or her job title, while in other cases, the job title could be inferred from the body of the message. We were able to identify clusters of librarians, retired-volunteers, engineers, students, artists, and reporters. This gave us a rough idea about what "other" stakeholder groups might exist. Next, we advertised to local communities such as libraries, schools, volunteer centers, art galleries and maker spaces, to offer workshops on 3D printable 3DP-ATPs at their sites. Our intent was to find a local representation of each of these other stakeholder groups in order to study them in depth.

Our outreach effort attracted six distinct local participant groups interested in running design workshops at their site, including a group of children librarians (n=6), a group of accessible media librarians, (n=6), a group of engineers with interest in supporting people with VI (n=3), a group of interaction designers interested in supporting people with VI (n=4), a group of volunteers who work at an accessible media library (n=7), and a group of TVIs and orientation and mobility (O&M) specialists (n=40).

4.2 Workshop Design and Analysis

Next, we describe the design of these workshops. The decision to conduct the workshops according to domain groups was driven by a desire to understand their perspectives deeply. We attempted to keep the basic structure of the workshop consistent across the various groups, but needed to customize some aspects of each workshop to better match a group's primary interests.

Critical Making: The goal of the workshops was not for participants to design a perfect 3DP-ATP or book; rather, it was to learn how people working with and for children with VI approach the task and apply their knowledge while using 3D modeling tools. Critical Making suggests that poignant selection of technology can empower people to fashion custom tools to accomplish specific tasks, visualize problems that are difficult to picture virtually, and to have fun by making their own toys (and learning aids). Specifically, 3D modeling and printing are tools to instigate new types of artistic and cultural expression, transformations of the notion of embodiment and materiality, renewed emphasis on the means of production, and the idea of a public good [33]. The design of our workshops was aimed at providing participants with an experience in the use of digital fabrication tools as a means for exploring, developing, and sharing their perspectives and values about the design task.

Hands-on Learning: Based on existing guidelines for teaching and learning tactile graphicacy, we took the applied arts approach of 'intelligent making' to support participant involvement. Intelligent making proposes a mix of formal knowledge, tacit knowledge, physical and mental skill, contextual awareness, innovation, and personal creative autonomy [13]. In crafting processes, the hands supply the brain with vital sensory information both inwardly from the external world and outwardly to enable the body to express the intentions of the maker. Hands are our primary interface with the world and provide the brain with rich sensory information, which is instrumental in building imagination and novel ideas [42]. Physical experience stimulates the imagination and provides anticipatory knowledge leading to performance in the creative act of making [40].

Structure: Each workshop was planned to last four hours based on the participant group leaders' recommendations. An hour and a half was allotted to introducing the design task, followed by two and a half hours of modeling/design work. The design task was scoped to focus on the transcription of existing pictures and books so that participants were not required to conceive of original drawings and narratives to support their compositions.

Each group was introduced to the topic by a sudden blindness activity, where blindfolded participants explored existing tactile graphics, pictures, and other materials through touch. In addition, examples of the tactile graphic guidelines and corresponding material were provided. Participants were then encouraged to analyze simple picture books such as *Good Night Moon* and *The Very Hungry Caterpillar* after a demonstration on how to decode such stories. Craft materials were also supplied for participants to rapidly explore their ideas in physical form. Each workshop was designed to incorporate the aforementioned elements; however, we allowed an adaptive workshop structure to suit each group's unique needs. Given the constructivist nature of the design task, we provided participants groups with opportunities to follow their own creative needs.

Technology: Prior to the workshops, our team completed a heuristic evaluation of five 3D modeling programs oriented to novice designers (Tinkercad, SketchUp, FreeCad, OpenSCAD, and 123D Design), their associated navigational and design tools, and their compatibility with producing STL files. The evaluation was conducted to inform the selection of the modeling tools to be presented and taught during the workshops. We used a five-point scale (1=intuitive, 2=easily learned, 3=moderate, 4=challenging, and 5=impossible) to evaluate the tools. We selected two tools to use during the workshops: Tinkercad (1.5) and SketchUp (2.5).

Figure 2 Workshop Activities: Discuss, Explore, and Model

Each group was provided an overview of the two selected 3D modeling environments. When participants were not familiar with the program, we guided them through the software installation process, demonstrated navigation, shape, and other tools within the interfaces, and in some cases provided follow-along instructions. We also gave a brief introduction to Thingiverse, an online STL repository and resource for finding, saving, and sharing models. Macintosh laptop computers and wireless mice were available for participants to use, and those with prior 3D modeling experience were encouraged to use their preferred software and tools.

Data Collection: During each workshop, we used discussion-motivated instruction methods to support participant inquiry and engagement in the design task. Numerous hands-on experiences were provided with existing tactile graphics and picture materials to allow participants to compare their touch-based experiences and reflect more deeply on the requirements of making tactile pictures. Field notes and video were employed to collect observations during both group discussions and talk-aloud activities during the modeling period to understand how participants were using their respective 3D modeling programs.

Analysis: Immediately after each workshop, we formalized our notes and recorded analytical memos that focused on participant concerns and considerations while approaching the design task and 3D modeling. After each workshop we used this information to improve the instruction of subsequent workshops, to identify each group's concerns and considerations while approaching the design task, which led to the finding that participant group have a unique approach to the design of 3DP-ATGs and may be able to take on different roles in a distributed design process.

Furthermore, when designing the workshops we understood that the task of designing and modeling 3DP-ATPs is complex and requires a range of skillsets to accomplish the task. We identified five skillsets: knowledge about human development (D), knowledge about emergent literacy (L), knowledge about tactile graphicacy (G), knowledge about task management (T), and modeling experience (M). After all of the workshops concluded we preformed a ranking of each participant group and their dominant skillsets among all participant based on observations of how they used the tools, related to principles of tactile graphicacy, referenced child development and literacy (1=low, 2=average, 3=high) (2). In addition to this ranking, we found clustering of skillsets, which provided deeper insight into how different participant groups can contribute to producing 3DP-ATPs.

5. FINDINGS: By Workshop Groups

5.1 Accessibility Librarians

Group Overview: Seven librarians from the Colorado Talking Book Library, where audio resources are recorded and provided to patrons with VI, participated in the workshop. The director of the library contacted us to inquire about our methods of creating 3DP-ATPs and to see if they were available for contribution. We agreed that a workshop would be a good way for the library's employees to learn more about 3D printing.

Prior Experience: The seven participants had a range of technology knowledge and skill for transcribing books into audio, but had no experience with 3D modeling, 3D printing, or transcribing books into a tactile format. Each participant was accustomed to interacting with visually impaired patrons at the library or on the phone daily.

Workshop Adaptations: Participants quickly lost focus and interest during the demonstration of 3D modeling, and asked to look at and touch some books prior to modeling.

Design Task Findings: The librarians spent an hour discussing the books (*Goodnight Moon*, *Five Little Ducks*, *Each Peach Pear Plum*, and *The Very Hungry Caterpillar*) and the constructs of a visual image and story. As a group they identified the graphical elements and discussed how to convey these elements through means other than sight. One librarian said, "*We should ignore elements of illustration that would distract from understanding the meaning of the story. We shouldn't worry about appearance as much as general shape."* When exploring how to convey emotion, another asked, *"Is a teardrop enough? Maybe this is a story where a paired reader is with the VI child to establish context."*

The group began to establish a set of their own guidelines to help with the task of transcribing illustrations, including: 1) observe the patterns of object/image repetition (e.g., movement, repetition, and progression); 2) take note of the social relationships established in the book's imagery and narrative; 3) observe how numeric and language literacy skills are being developed; 4) observe how emotions are conveyed in the story; and 5) recognize the historical and cultural context of the book and make representations that are relevant to a child's current context. The Talking Book librarians also reflected on the philosophical challenge in prioritizing illustration over text and the challenge to think about honoring the perspective of a person with VI.

Modeling Task Findings: In order to simplify the modeling work, we opted to demonstrate how to import models from Thingiverse into TinkerCad and subsequently how to use the tool to compose a page of tactile elements. All participants collectively elected to model one page from *Goodnight Moon* by ignoring elements of illustration that distract from understanding the meaning of story. One participant suggested that, *"We should not worry about appearance as much as general shape."* While importing models from Thingiverse into TinkerCad and trying to place them on the "page" all participants struggled with differentiating between scaling and moving an object vertically. The use of navigation and orienting tools to improve the modeling experience was unintuitive for the participants. Some had difficulty using the zooming feature, while others were confused about saving and accessing their models on TinkerCad. Despite the fact that most of the participants struggled to get "*the program to do what I wanted it to do,"* all were satisfied with the experience at the end of the workshop. One librarian said that, *"This technology has a lot of potential for helping our community access their world."*

5.2 Children's Librarians

Overview: The Boulder Public Library acquired a new 3D printer for their teen makerspace and reached out to our research team to learn more about the applications of the technology. Eight early-literacy librarians who were knowledgeable about reader engagement, literacy development, and children's books were keen to develop literacy-based materials and 3D print.

Prior Experience: Aside from the workshop coordinator, none of the librarians had previous 3D modeling or printing experience. All of the librarians worked with young children and their families' daily; they had infrequent visits from blind patrons.

Workshop Adaptations: Prior to the workshop, the library coordinator proactively created a plan to follow in order to maximize the use of time. She also began a conversation with her coworkers in preparation for the workshop, during which the librarians collaboratively chose three books to model: *Windblown*, *Where the Wild Things*, and *Anton Can Do Magic*. The books were selected because they represented three different reading levels and communicated the Every Child Ready to Read (ECRR) principle of "Play". Play was chosen as a central topic because of the embodied attributes of the theme and the opportunities for representing interactivity in a variety of ways. When describing their rationale for this during the introduction, one librarian explained that, *"some books are interactive. We see animals jump out of the page…books that really want the kids to come into the books and also the characters to go out."* The participants repeatedly emphasized that the storytelling aspect of the design task was as important as representing objects in 3D.

Design Task Findings: During the entirety of the workshop, the librarians continuously brainstormed about opportunities for 3D printing in their libraries beyond tactile books, including: 1) creating open-ended toys (additive toys where evolving experiences and scenarios allow the child to be the instigator); 2) creating interactive wall installations and shadow puppetry; and 3) developing a prompt for local authors to produce original work paired with 3D model illustrations in association with National Novel Writing Month in November.

As we described and explored the tactile graphic guidelines, the librarians explained how illustrations were carefully composed to tell an important part of the story, and how original artistic choices were important to the narrative. One participant was very interested in, *"thinking about how to maintain the integrity of the original work; the pictures aren't just illustrating the story, they are telling the story."* For example, the librarians explained that in the case of *Where the Wild Things Are*, as the main character becomes increasingly engrossed in the world of the Wild Things, the images increase in size. Another librarian pointed out how some illustrations make readers interact with the book in different ways. In some instances, book illustrations require one to turn the book's page in order to become part of the story environment. Other book illustrations focus on engaging readers in their immediate surroundings.

Throughout the modeling work, the group paused multiple times to discuss the key challenges and advantages of using 3D printing as a medium for approaching the design task. They were engaged with the materiality of the books as well as the content, deliberating on how to transcribe a detailed picture while simplifying it for printing. The librarians referred to the decoding and abstraction of the images, and discussed the advantage of graphic novels in the balance between graphical simplicity and conveying concepts. Size optimization was also taken into consideration as they considered both printer limitations and the

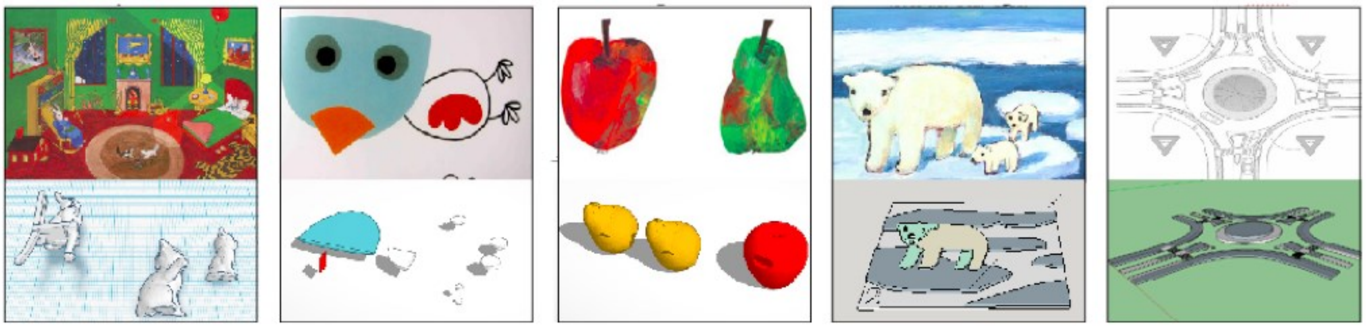

Figure 3 Examples of Workshop Groups' Models. (From left to right) Accessibility Librarians, Children's Librarians, Engineers, Interaction Designers, O&M/TVIs. (Volunteers did not produce any models).

fact that larger formats are easier for younger tactile learners. Finally, 3D printing was suggested as an activity to engage parents in storytelling. One librarian said that, *"the material act of transcribing the book would help a sighted parent think about her child's experience."*

Modeling Task Findings: Participants began modeling individually, but eventually decided to work in pairs. At the end of the workshop the group gathered to focus on modeling a "package" of models that could be used in different configurations to represent different concepts in a book. In doing so, they explored how some stories are not linear and that moving parts may provide a richer experience. While modeling in TinkerCad, participants had difficulty distinguishing between icons for rescaling objects and moving them vertically in space. They exhibited a lack of knowledge about the use of navigation tools to orient their work in space and had difficulty learning the techniques of the 3D modeling environment, such as reorienting objects from different angles. Finally, there was some confusion on the effects of grouping objects and how to select multiple objects at once. When the librarians encountered a problem with the software they verbalized the challenge, and the group often discussed solutions collectively. Most participants left with a sense of gratitude, while acknowledging that more practice would be needed with the program to achieve the design task, although they were more inclined to help with future book selection and activity creation efforts than model design.

5.3 Talking Book Library Volunteers

Overview: Seven volunteers from the Colorado Talking Book Library attended this workshop, which was organized by the director of the library (similar to 5.1). All participants were retirees, who collectively had years of experience in contributing to the library's effort to translate books into an audio format. The director of the library strategically recruited these volunteers for the workshop because of their long-term contribution to the library, and their perceived abilities and interests in technology in general.

Prior Experience: While none of the volunteers had experience with 3D printing, three had used 3D modeling programs, and several others had extensive experience with audio recording and transcription technology. All of the participants interacted with blind patrons at the library. One of the participants had a blind spouse, while another referenced his children and grandchildren's experiences using 3D printers as his motivation for attending the workshop, and the others attended to help support the library.

Workshop Adaptations: In order to focus the group conversations about transcription onto a concrete task, participants were challenged to select images from *Goodnight Moon* and find a model on Thingiverse that they thought would be accessible through touch. When working in TinkerCad, we focused on participants' efforts to navigate the screen and move forms.

Design Task Findings: The volunteers focused much of their conversation on the strategies used at the library to make content accessible. They spent little time critiquing the pre-fabricated models, but discussed how audio-transcription guidelines might be used to help with visual-to-tactile transcriptions. During the overview of the 3D modeling software, the library volunteers focused on the the applications of 3D modeling; they were most concerned with how people use different types of media, but were reluctant to go deeply into the design process and consider how to transcribe the materials.

Modeling Task Findings: In order to engage the participants in the design process we opted to spend more time walking them through the 3D modeling and printing ecosystem and helping them set up accounts on Thingiverse and TinkerCad. This process took nearly an hour. Several people were worried about setting up accounts, and one participant sent an email after the workshop saying, "*I resent having to set up an account with the CAD software...it was a great experience - just not my "cup of tea" for in depth participation."* Another repeatedly said that, "*I can't do this, I am not good with the computer."* When using TinkerCad, all participants had difficulty distinguishing between the icons for scaling and moving an object in space. One participant could not understand why objects "got bigger" as they moved across the page, and despite attempts to explain the idea of perspective within the software (closer objects appear larger), they ignored suggestions to rotate the page to a bird's-eye view for more intuitive object behavior. Compared to other groups, this group received the most guidance due to frustration with the software.

5.4 Engineers

Overview: After a local hacker/makerspace learned of our research, they offered to run a workshop for their members. Three hackers responded to the invitation, and all identified themselves as engineers. Due to the small group size we observed each participants' work as opposed to as a group.

Prior Experience: The three engineers had greatly varying familiarity and comfort with 3D modeling. The most confident modeler (Participant A) worked with SolidWorks on a daily basis as part of his job designing medical tools. Participant B was identified himself as a 3D modeling hobbyist and was most comfortable working in Sketch-Up. Participant C indicated that he had used a 3D modeling program once or twice before. All three participants were motivated to join the workshop due to previous experience living or working with people with VI or cognitive disabilities. They all expressed interest in contributing to efforts that led to equal access, though non of them had previously made ATGs or ATPs. At the beginning of the workshop each person shared their personal experiences with friends and family members who have VI.

Workshop Adaptations: The introduction and technology overview were cut short due to Participant A and B's eagerness to start using the modeling software and work independently. In turn, we spent a considerable amount of time helping Participant C become familiar with TinkerCad.

Design Task Findings: Despite the range of technical experience, all three participants' design processes and decision-making were heavily mediated through the 3D modeling tools they used. Participant A quickly chose to design pieces of fruit from the book *Each Peach Pear Plum*, and focused on creating an exact representation of the fruit. Several times through the session he discussed the challenges of modeling, as opposed to focusing on the challenge of transcribing the images. He explained that, "*the reality of it is any parent with a disabled child isn't going to have the time to sit and model, unless they do that for a living.*"

Participant B brought in a book to model from and had been practicing using SketchUp in preparation for the workshop. He had decided on a strategy for completing the design task beforehand by scanning images of the book to import into SketchUp. *The Giving Tree* was one of his favorite books. "*I want to convey the relationship between the boy (who becomes a man) and the tree. It is about love, the environment, and time.*" When describing his design process, he said that, *"the story didn't need to be told page-for-page. As long as the message gets conveyed, I feel the volume of content printed is unimportant."* While not focusing on decoding, specifically, it was evident that he was thinking about the way content was portrayed, how to simplify difficult concepts into more basic representations.

After facing difficulty with the learning the 3D modeling programs, Participant C eventually chose to represent three bears sitting on chairs from *Goodnight Moon.* He first created a storyboard to distill the concepts of the book and chose to focus on the concept of bears sitting on chairs. Of all the participants, he focused on the particular learning purpose of the model the most.

Modeling Task Findings: During the modeling work there was very little dialogue between participants; one elected to put on headphones. However, when prompted, all were happy to help each other problem-solve while modeling. Participant A focused much of his time on identifying how to use the 3D modeling tool most efficiently to achieve the task. By using various geometric line tools alongside the extrusion tool, he was able to 3D model a pear and an extruded an apple. He focused on making sure edges were rounded due to his concern about the feeling of the plastic on a child's finger. It was evident that he was learning through trial and error, and by the end, his models of the illustrated fruit closely represented the images portrayed in the book.

Similar to Participant A, Participant B focused his modeling on how to leverage the efficiency of using SketchUp to transcribe an image. Using the rescanned images of the book, he used the freehand tool to define the shape of his model. He used the copy/paste tool to render the many leaves on the tree before extruding them all at once. Due to difficulties with downloading and loading SketchUp and creating an online account for TinkerCad, Participant C began modeling with clay. When referencing the 3D modeling program, he said, *"I thought it would be a simple thing—I'd just start a project and it'd just be flowing, and it suddenly is not…I'm feeling very frustrated."* Despite the differing modeling styles, each participant was innovative in their solutions (whether switching media or using different modeling methods), and was proud of their final representations.

5.5 Interaction Designers

Overview: Four interaction designers with experience with education technologies and material design participated in a workshop. They learned about the research through a colleague and wanted to engage in a making task that had social implications, while learning more technical skills.

Prior Experience: Three participants had never used a 3D modeling application, while the fourth had extensive modeling experience with Maya. Of all of them, only one had used a 3D printer. The three inexperienced participants chose SketchUp because it provided an option to use the mouse to draw lines and irregular shapes, while the experienced participant chose Maya. None of the participants had experience spending time with children with VI, but two had young children and were motivated to participate to explore the use of tactile pictures in their homes.

Workshop Adaptations: After initial introduction activities, we worked more in-depth with this group to develop modeling skills. All participants had 3D modeling programs preinstalled on their computers. The Maya user was eager to start modeling and urged the others to use their experiences to inform their ideas.

Design Task Findings: Several participants brought in their favorite children's books, but the group opted to work together to complete one book, *Mommy Loves*, because they were concerned about the time it would take to complete the design task. They divided the pages up, defined a template for the page size, and collectively decided where to put text on the page. They all worked independently and remained focused on the task until the end of the workshop.

While working, the group continuously provided suggestions for how to achieve the design task, such as how to break the design task down into simpler parts by dividing up the tasks by specialty. One commented that, *"the most effective approach to designing a tactile page is not by giving the whole task to a 3D modeler initially, but to design with other materials…to identify key characteristics of the book, and then passing that off to a modeler."* When asked whether they were interested in learning more about designing for people with VI, one responded, *"Even with professional experience with modeling animations with Maya, I realize that this field is huge and requires depth/professional efforts in it."* Many of the group's design process and design-based decisions were focused on how to manage the task.

	A	B	C	D	E
	Group	N=#	Knowledge	Design Thinking Focus	Design Task Requirements
5.1	Accessibility Librarians	7	Media Access & Distribution	• Focused on use of existing guidelines • Focused on understand theoretical implications of transcription	• Include/honor skills of people with VI • Choose relevant (time/context) representations of information
5.2	Children's Librarians	6	Emergent Literacy	• Focused on individual learning needs • Focused on task management, community support and collaboration	• Design simple features around a concept • Consider artists' original work
5.3	Library Volunteers	7	Audio-Transcription	• Focused on novelty of the technology • Focused on how to facilitate end use	• Consider the use of audio formats to complement the 3DP-ATP
5.4	Engineers	3	Design and Engineering	• Focused on efficiency of modeling • Focused on complexity of modeling	• Have a realistic view of the work • Focus on the book's learning goals
5.5	Interaction Designers	4	Interaction Design	• Focused on management of design task • Focused on defining new design methods	• Create templates to increase efficiency • Parse the design task according to abilities
5.6	O&M/ TVIs	40	Vision Sciences	• Focused on adhering to guidelines	• Understand the child's learning context • Include VI people in the evaluation

Figure 4. Findings by Workshop Group

<u>Modeling Task Findings</u>: The participants using SketchUp immediately became frustrated by the unintuitive nature of the icons and the "unexpected" behavior of navigation. However they tried to work through their problems by finding alternatives. For instance, when one participant struggled to model something that looked like the illustration, they elected to take a picture of the illustration and import it into SketchUp to trace over. After this, each participant opted to work with the freehand drawing tool to transcribe a two-dimensional representation of an animal, followed by using the extrusion tool for the 3D representation. All participants found the freehand tool frustrating due to the lack of control one had using the mice as a pen or brush. Participants also found it difficult to close these free-drawn lines because the point of origin was difficult to distinguish. Participants were dissatisfied with the hard edges from using the extrusion tools.

Two of the participants lost motivation to complete the task due to the seemingly insurmountable barriers presented by the technology. *"I realized the limitations and frustrations in technology as part of the creative process...even learning the options for how to maneuver were not intuitive!"* This participant also had experience sculpting and was more accustomed to using her hands to produce work. By the end, the all four participants produced a model of a unique page in the book.

5.6 O&M Specialists and TVIs

<u>Group Overview</u>: Forty orientation and mobility (O&M) specialists and teachers of the visually impaired (TVIs) participated in a workshop conducted in conjunction with a Department of Education (DoE) teacher training workshop. The coordinator for the training requested the workshop after receiving requests from teachers to learn more about 3D printing.

<u>Prior Experience</u>: All of the participants had experience making ATGs and teaching K-12 students with VI. Only one person in the crowd had used 3D modeling software and 3D printers.

<u>Workshop Adaptations</u>: The DoE coordinator asked to have a demonstration on how to use 3D modeling programs to transcribe images of road intersections due to the fact that various types of intersections that can make way finding difficult for older students. While this task and modeling work focused more on the design of 3D-ATG maps than the design of 3DP-ATPs for emergent literacy, we chose to include these findings because much of the discussion-based data we collected pertained to 3DP-ATP. During the introductory activities, we created a 3D modeled tactile intersection template, and showed the participants how to construct a basic intersection based on a picture. We then presented pre-fabricated 3D printed tactile copies of Good Night Moon and prompted the participants to critique it. The group elected to break up into teams of four to model using SketchUp.

<u>Design Task Findings</u>: While working in the small groups, many of the participants began by sharing ideas for how to use 3D printers. One person noted that, *"tactile pictures with raised lines could be great for tactile coloring books, not for rendering concepts like background and foreground."* Another person was thrilled by the possibility of making a replacement for a special tactile book she used with a student. "*I have searched and searched for this grommet-shaped part for my book…I can't believe how much time this will save."*

While examining the pre-fabricated 3D printed tactile picture books, many people referenced known guidelines. "*Be aware of the amount of space you are putting around the objects. It's difficult to feel small objects on a flat space when you aren't aware of the story being told."* They indicated that it is important to design materials to complement the child's immediate environment/routines, with particular focus on basic experiential concepts, spatial relationships of objects on the page, and a progression of materials and activities that help develop finer tactile acuity. One person said, "*The most important thing is to keep the models simple and make sure that you work with the student to make sure they find the tactile picture makes sense to them. People learn to make sense of what is around them. Don't assume when you introduce a new tactile it will immediately make sense."* Throughout the workshop many of the O&M and TVIs advocated for involving children with VI to evaluate whether the models were accessible. *"Get more blind people involved with testing the models and graphics because they will be able to provide more useful feedback than a sighted person because they are more informed about what they need."*

<u>Modeling Task Findings:</u> In almost all groups, one person became the lead modeler, while others observed, discussed, and gave advice regarding their work. Those who spent the majority of their time modeling focused on learning how to make simple shapes and to navigate the modeling environment. They expressed frustrated with not knowing where to find the design tools within the menus. One modeler expressed hesitation about the

technology, saying *"maybe I am interested in 3D printing for tactile graphics in a progress kind of way, but for our district it is not practical right now...it needs to become easier."* We heard this time and time again. No team produced a complete model.

Still, the majority of the O&Ms and TVIs remained positive about 3D modeling and printing technology. One person reflected that she could now create something she had been trying to find for years. Another said, *"I just can't wait to learn how to apply this technology, and visualize all the possibilities."* However, there was a generational divide between those interested in 3D modeling and related software, and those who felt that it was too complicated. One participant commented, *"I am about to retire. This technology is for the next generation to pursue."* Many teachers discussed available time being a deterrent to learning how to model, along with the lack of resources and time to participate in technology workshops.

6. FINDINGS: Across Groups

Above we summarized how each participant group approached the design task. Here we observe which aspects of the task they focused on and the associated design requirements. We note that participants approached the work according to different roles.

6.1 Designer Roles

Each group that we worked with focused on different aspects of the design task and revealed a series of requirements for creating 3DP-ATPs. Among the 67 participants, four primary ways of approaching the task surfaced. Some participants focused on developing materials to support individual needs, some focused on the creation of guidelines, while others focused on the theoretical implications. We identify these roles as:

<u>1) End-User Advocate</u>*:* During our workshops, those who work with people with VI on a regular basis (O&M specialists, TVIs, and Accessibility Librarians) strongly advocated for designing content that is both specific to individual children while adaptable to suit other children's needs. They emphasized the importance of knowing the child's cognitive ability and VI prior to modeling. These participants also designed, referenced and applied existing guidelines for ATGs/ATPs, indicating that this is standard practice within the profession. In cases that they were not aware of existing ATG guidelines, they attempted to create their own, exhibiting an understanding of how to scaffold a VI child's learning by describing specific model characteristics and identifying the appropriate levels of storytelling.

<u>2) Content Translator</u>*:* The early childhood librarians and accessibility librarians displayed an ability to apply their knowledge on emergent literacy, exhibiting a range of skills necessary for unpacking and abstracting content, and advocating for artistic intellectual property rights. They approached the task with a strong focus on how to decode visual illustrations and the meaning they convey. They emphasized how the composition of elements on a page creates a graphic narrative, and concentrated on discussing the phenomenological aspects of transcribing across the senses. These participants also placed greater value on whether or not authors' original intent and artwork are fairly represented, and made recommendations for how to look at the whole of the stories and decode certain elements, a value we did not observe in other groups. They also valued how material artifacts are used appropriately to engage children in meaningful ways, and how materials can be used to support joint attention (for emergent literacy). Most recognized that in some instances 3DP-ATPs might not convey the totality of the original author or illustrator's intent. There are trade-offs that must be considered.

<u>3) Task Manager</u>*:* The librarians also showed strong organizational skills around task management and book selection, which enabled them to quickly select and analyze the structure and components of the book, and communicate about important aspects of the transcription task. They emphasized the consideration of original artists' work and design communication (the concept, sequencing, and interactivity) efforts, in turn weighing the trade-offs between simplifying graphics and staying true to the original illustrations. They also recommended blending media to make the most appropriate representation of the information. The interaction designers exhibited a similar organizational and management ability, however they tended to look at the entire scope of the of the design task, in turn parsing out different aspects of the work to different collaborators. Their exhibited a meta-level review of the design task while modeling.

<u>4) Modeler</u>*:* The participants with previous modeling and design experience (engineers and interaction designers) showed the ability to problem-solve within the 3D modeling environments. They wanted to start by modeling with tools and discuss their approach/challenges/successes with the design task in progress, as opposed to the less technically experienced participants who spent more time analyzing the task prior to trying the programs. They tended to focus on how information was communicated through form, but not specifically on how to make the information accessible. They quickly identified the complexity of the design task and made recommendations for how to improve efficiency while modeling, and how to scope and manage the work.

6.2 Underlying Skillsets

As described in Section 4.2, after all of the workshops concluded, we ranked each participant group's dominant skillsets according to five criteria to further evaluate and summarize the strengths of each participant group: (1) Human development, (2) Emergent Literacy, (3) Tactile Graphicacy, (4) Task Management, and (5) Modeling. (Figure 5). No single group has skillsets across all five categories. Each workshop group that elected to participate in this study (except for the volunteers) showed strength in two or three skillsets, for example, the TVI's (4.6) showed strength in demonstrating and applying knowledge about human development and tactile graphicacy during their design work. Each workshop group had a different coupling of skills. These findings have implications for future work, as discussed in the next section.

	Workshop Group	D.	L.	G.	T.	M.
4.1	Accessibility Librarians	3	3	2	2	2
4.2	Children's Librarians	2	3	3	3	2
4.3	Library Volunteers	2	1	1	1	1
4.4	Engineers	1	1	2	1	3
4.5	Interaction Designers	1	2	2	3	3
4.6	O&M/TVIs	3	2	3	2	1

Figure 5. Skillsets by Workshop; D= Human Development, L= Literacy, G= Graphicacy, T= Task Management, M= Modeling

7. DISCUSSION AND FUTURE WORK

The space of designing ATGs and ATPs has existed for some time, but using 3D fabrication tools to create and design these materials is still a new field. To the best of our knowledge no other study has systematically reported on how non-professional modelers, transcriptionists, and tactile artists use the personal fabrication technology to create 3DP-ATPs. During our participant recruitment it became obvious that TVI's and O&M

specialists, librarians, interaction designers, engineers, and other volunteers, with varying skillsets, are interested in creating 3D-ATPs for children with VI. Some of the 67 participants joined the workshops due to a personal connection with somebody who is blind. Some joined as a way to increase their exposure to emerging technology, and others joined simply to contribute their skills to a meaningful cause.

We designed the workshops to introduce participants to the task and to mitigate the known barriers to designing 3DP-ATPs for the first time. Depending on their experience we provided overviews and hands-on instruction of 3D modeling programs, examples of ATGs, ATG guidelines, sudden blindness experiences, lessons in decoding and abstraction, etc. Each of the groups approached the task of creating 3DP-ATPs from a different perspective. We identified the dominant focuses in each group's design thinking, e.g. Accessibility Librarians= Focused on use of existing guidelines, and focused on understand theoretical implications of transcription (Column D, Figure 4). Each participant group's design thinking focuses and associated requirements indicate that people elect to take on a specific role in the design process: End-User Advocate, Content Translator, Task Manager, or Modeler.

Nonetheless, we noted that designing from just one of these roles or perspectives did not prove to produce a meaningful 3DP-ATP; 3DP-ATPs produced by a person with exposure to only one or two skillsets may fail to make a 3DP-ATP that tacitly communicate what is important to a child's learning. Despite our efforts to mitigate the challenges of creating 3DP-ATPs, many of the caregiver and stakeholder groups did not innately recognize the full scope of what is required by the design task or know how to apply existing ATG guidelines, and tended to stay within their domain-based comfort zones. This begs the question of whether 3D modeling and printing can be successfully leveraged by caregivers and stakeholders, who often have limited time and resources to learn new skills, for the creation of ATPs and ATGs? We believe that caregivers and stakeholders have critical knowledge to contribute to the design task, and given the right recourses will be able to create 3DP-ATPs. However, this will require making the design task more approachable to amateur makers and leveraging caregivers and stakeholders existing skillsets and motivations for creating meaningful 3DP-ATPs.

7.1 Design Activities & Associated Roles:

Participants offered valuable advice for how to make the design task more approachable. Their recommendations fall into four different categories that parse the task into activities. Each of the activities correspond to one of the four key design roles caregivers and stakeholders are prone to take on while approaching the task.

Activity A- Need Assessment and Evaluation: Understand the child's learning context at the onset of the design process and include people with VI in the evaluation of the models. → *End-User Advocates'* skills can be used to validate printable tactile pictures modeled by others for composition and tactile detail, to identify 3DP-ATP projects for specific children, and to coordinate the inclusion of end-users and caregivers in evaluation.

Activity B- Content Selection: When selecting content to translate, consider the meaning associated with the artists' original work, choose books according to the intended learning goals, and consider the use of audio formats to complement the 3DP-ATP. → *Content Translators' s*kills can be used to help select books, identify the project scope with initiators, and edit content to enhance how designs are communicated across the senses.

Activity C- Representation: When designing content, choose relevant (time/context) representations of information and design simple features around a single concept. → *Task Managers'* skills can be used to help determine the sequences in which design activities should occur in the process of creating an 3DP-ATP, and to provide assistance and explicit instruction to each of the other team members—particularly the modelers.

Activity D- Production: When creating models, begin with a realistic view of the work and possibly divide the design task according to abilities, and create templates to increase efficiency. → *Modelers' Skills* can be used to develop guidelines and easily replicable samples of work, along with the task manager to engage in the design cycle with the others.

7.2 Collaborative Design Platform

The aforementioned recommendations for parsing the design task and ways using one's skill to contribute to the creation of 3DP-ATPs can be used to inform how participants interact while collaborating to create 3DP-ATPs. However, similar to the existing ATG guidelines, this information alone may not adequately prepare caregivers and stakeholders to contribute their skillsets in a collaborative fashion. In turn, we propose the design of a digital fabrication tool to unite designers from different disciplines around 3DP-ATP projects, while providing individuals to use their skills to make meaningful 3DP-ATPs.

This future research task treats the design of 3D-printed ATPs as a collaborative, transferrable process inclusive of a broad range of stakeholders including parents, teachers of the visually impaired (TVIs), librarians, and other community volunteers. Based on the findings of this study, we anticipate that an online, 3DP-ATP collaborative design platform may include features that enable people to: 1) build teams of designers; 2) propose design projects; 3) notify participants of project activities; 3) visualize progress and task allocation; 4) support communication between different team members; and 5) scaffold designers learning about ATG and ATP guidelines. We anticipate that a tool of this nature will require community management, and will look to the literature on social computing and creativity support tools to inform future designs. From findings presented in this research, we anticipate that children's librarians and TVIs would be the early adopters in order to rally other community members to help make 3DP

We plan to run additional workshops to help form multi-disciplinary teams of participants representing each of the identified roles. The aim of this research will be to identify how the team members collaboratively approach the task, whether multi-disciplinary teams disrupt the notions of the roles we present here, and what unique interface features will support their synchronous and asynchronous collaboration. To date we have not encountered teams of 3DP-ATP designers in the wild, however many caregivers identify the need for more shared resources on the design of accessible 3D material. We hope through the creation of such a tool will enable such a community to emerge.

8. CONCLUSION

In this paper, we presented insight about how six groups of stakeholders of children with VI approach the design task of 3D modeling accessible tactile pictures. Workshop participants demonstrated that the design task requires five different skillsets: disability science, literacy, graphicacy, project management, and 3D modeling. Of the 67 research participants we worked with, no one exhibited all skillsets. However, we identified that participants typically approached the design task from one of four roles: end-user advocate, content translator, task manager, or modeler. Each participant group specified requirements for approaching the design task from these associated roles, which we used to establish a framework for how caregivers and stakeholders can collaboratively design 3DP-ATPs. Future work will focus on assessing how multidisciplinary teams approach the work and how to develop creativity support tools to involve various stakeholders, and how to develop a collaborative design platform for the creation of 3DP-ATPs.

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