# Investigating the Implications of 3D Printing in Special Education

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Consumer-grade digital fabrication such as 3D printing is on the rise, and we believe it can be leveraged to great benefit in special education. Although 3D printing is infiltrating mainstream education, little research has explored 3D printing in the context of students with special support needs. We describe our studies on this topic and the resulting contributions. We initially conducted a formative study exploring the use of 3D printing at three locations serving populations with varying ability, including individuals with cognitive, motor, and visual impairments. We found that 3D design and printing perform three functions in special education: (1) STEM engagement, (2) creation of educational aids for accessible curriculum content, and (3) making custom adaptive devices. As part of our formative work, we also discussed a case study in the codesign of an assistive hand grip created with occupational therapists at one of our investigation sites. This work inspired further studies on the creation of adaptive devices using 3D printers. We identified the needs and constraints of these therapists and found implications for a specialized 3D modeling tool to support their use of 3D printers. We developed GripFab, 3D modeling software based on feedback from therapists, and used it to explore the feasibility of in-house 3D object designs in support of accessibility. Our contributions include case studies at three special education sites and discussion of obstacles to efficient 3D printing in this context. We have extended these contributions with a more in-depth look at the stakeholders and findings from GripFab studies. We have expanded our discussion to include suggestions for researchers in this space, in addition to refined suggestions from our earlier work for technologists creating 3D modeling and printing tools, therapists seeking to leverage 3D printers, and educators and administrators looking to implement these design tools in special education environments.

CCS Concepts: • **Social and professional topics → People with disabilities**

Additional Key Words and Phrases: 3D printing, assistive technology, children, cognitive impairment, digital fabrication, developmental disability, rapid prototyping, special education, visual impairment

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## 1. INTRODUCTION

Three-dimensional (3D) printers are a promising technology gaining acceptance in mainstream education as a means to engage students with hands-on interactions [Tides Center 2014]. However, little has been published on the role of this technology in special education. We feel this technology can contribute to special education through (1) supporting STEM (Science, Technology, Engineering, and Math) engagement in a historically underserved population, (2) creating curricular materials, and (3) creating assistive technology (AT).

3D printing technology can offer students a powerful tool for creativity and exploration and an engaging introduction to STEM topics. For example, students can print simple machines to help visualize elementary concepts in physics and engineering or design their own small-scale buildings as part of an architecture lesson. Finding ways to increase participation in science and engineering is a universal challenge, but it is particularly important for students with disabilities, as they are severely underrepresented in these disciplines [National Science Foundation 2013].

Customized learning aids in the classroom and individualized assistive technology are both possibilities for 3D printing in special education. In the classroom, for example, a history teacher could download an open-source model of a pharaoh's tomb and have a durable plastic diorama, which would be content specific and could be handled, helping students with visual impairments as well as tactile learners. In the case of assistive devices, a therapist could use a 3D printer to create a custom tablet mount for a wheelchair, tailoring the design to both the tablet case and the individual student's chair, circumventing purchasing processes and exorbitant costs. In order to achieve these goals, special education institutions must first gain access to 3D printing technology and then make the time to learn how to use, operate, and maintain this equipment.

To understand how special education institutions are currently using 3D printing technologies, we studied three organizations providing special education and technology access services. We observed a classroom and conducted interviews with teachers, therapists, administrators, and technical experts. We worked with two schools that support middle- and high-school-aged children, one focused on students with cognitive impairments and the other on students with vision impairments. Our third site was the technology division of a national organization offering training and support to blind individuals. Our analysis revealed insights into the current uses of 3D printing in special education and how we can better support its use.

Based on observations and interviews at our main investigation site, we identified a potential project leveraging 3D printing for the creation of assistive devices. We engaged in an iterative codesign process with occupational therapists from that site to explore this application of the technology. The codesign process resulted in a case study exploring 3D printed objects as assistive devices and was the motivation for GripFab, a prototype design software intended for the simple creation of 3D printed objects to support persons with limited dexterity and gripping ability. The software requirements were derived from therapist feedback and the prototype software was brought back to therapists twice for evaluation and to evoke further discussion of the merits and potential problems related to in-house or self-designed assistive objects.

In this article, we first summarize existing research on 3D printing in education, DIY accessibility, and learning. We describe our investigation into the current use and practices of 3D printing at three sites and present each investigation site as a case study. We extended our original work [Buehler et al. 2014] by describing the expectations and perceptions of 3D printing from the perspective of multiple stakeholders in special education. We also introduce GripFab, a specialized piece of modeling software to create custom hand grips that was designed for clinicians at one of our investigation sites. We present applications of this prototype software and we discuss the opportunities and challenges involved in efficiently implementing 3D modeling and printing for special education use. Finally, we offer revised suggestions for future designers and technologists in this space, as well as our lessons learned related to 3D printing in special education environments for therapists, educators, and researchers.

## 2. RELATED WORK

Our research builds on existing explorations of making in children's education, Do-It-Yourself (DIY) assistive technology, and Universal Design for Learning. We briefly describe relevant work from these topics to help frame our research goals next.

### 2.1. Education and Making

With the rise in personal fabrication, there has been an increased interest in how children can interact with fabrication technologies. Encouraging engagement in STEM fields is a prevalent topic in education and one that researchers in our field are addressing using digital fabrication. Leduc-Mills and Eisenberg [2011] have developed a series of technologies and conducted workshops on involving children in 3D design. They developed the UCube [Leduc-mills and Eisenberg 2011], which is a tangible interface for designing objects in three-dimensional space. Researchers have conducted workshops to explore the implications of making in the classroom as a reinvention of constructionist learning and discussed the accessibility of tools for children in mainstream contexts [Blikstein and Krannich 2013; Krannich et al. 2012; Leduc-Mills et al. 2013]. Posch and Fitzpatrick [2011] also conducted an extensive series of workshop studies exploring children's expectations and outcomes when using 3D design tools. These workshops used open-source tools and personalized take-home projects, finding that "An especially crucial factor for the children's sense of satisfaction appeared to be the technical challenge and mastery of the task and the personal engagement associated with the result." Additionally, we are starting to see books published on the topic of making and DIY skill building for children [Kemp 2013; Libow et al. 2013]. Again, these focus on constructionist learning and STEM engagement.

Our study supports and extends this work by furthering the understanding of educator perspectives on making in the classroom, as well as examining the needs of students with disabilities both in terms of value gained from making and their access to this new wave of digital fabrication. We extend our prior work [Buehler et al. 2014] in this area by providing more in-depth discussion of the educator and administrator perspectives on 3D printing in special education.

### 2.2. Making and Assistive Technology

DIY fabrication addresses two important issues in assistive technology—cost and customization. Financial costs of the device and assessment can be astronomical for the average user. Proper fit and personalization are key issues in AT abandonment. With 3D printing, end-users can create their own custom designs at reduced cost [Hurst and Tobias 2011]. Brown and Hurst's [2012] VizTouch software creates 3D printable tactile mathematical graphics for use in accessible education and business. Finally, Hurst and Kane [2013] offer example tools designed to make DIY more accessible to a variety of populations, including encouraging children in STEM topics [Kane and Bigham 2014].

Creating assistive technology for children raises additional challenges that must be addressed before children will adopt these technologies. Several of these challenges are highlighted in the works of Dawe [2006] and Copley and Ziviani [2004], in which barriers to adoption are identified with respect not only to AT devices but also to the people and environments surrounding young users. The exploration of Hayes et al. [2010] into visual support for children with autism uncovered other key factors related to children and AT. Children change and outgrow devices very quickly, which can lead to problems when being fitted for these items. These problems include the manufacturing time for custom-ordered devices and prolonged waiting periods for paperwork processing between medical/insurance providers and manufacturers when ordering generic items. Another aspect of AT adoption versus abandonment is the perception of others. Children are susceptible to popular opinion and the sense of belonging, making the stigma around AT a serious issue.

In our earlier work, we investigated how 3D printing can address these concerns in the context of special education, providing inexpensive and customized solutions for young students [Buehler et al. 2014]. This article extends our prior work, including additional findings regarding the stakeholders in this setting and the presentation of a prototype study examining a novel software design tool, GripFab, targeted to occupational therapists. We also expand on our discussion and provide further suggestions and insights regarding these technologies.

### 2.3. Universal Design for Learning

Universal Design for Learning (UDL) research has explored the use of tangible learning aids for students with varying abilities. UDL is an extension of universal design for accessibility applied to education. UDL follows three guiding principles: (1) flexible methods of presentation, (2) flexible methods of expression and apprenticeship, and (3) flexible options for engagement [Rose et al. 2002]. By offering educators a way to create their own 3D printed objects, they can in turn offer multimodal interactions for their students. The benefits lie in presentation of information and demonstration of knowledge gained. A student with a visual impairment may gain access to graphical information tactilely, or a student with a cognitive impairment might demonstrate math skills by manipulating objects rather than writing out equations. When discussing multimodal interactions, the concept of tangibles is a natural connection. Manches and O'Malley [2011] provide an extensive review on the topic of tangibles and manipulatives in education and how to support these interactions.

Our research examines the potential for 3D printers to assist with the creation of educational aids, adaptive devices in support of learning, and manipulatives—physical objects designed to promote comprehension through interaction. We also present expectations and perceptions of faculty and staff in special education settings. In extension of our prior work, we document applications of 3D printing as suggested by special education instructors.

### 2.4. State of 3D Modeling and Printing Technology

In order to create an object to be manufactured on a 3D printer, one needs a 3D model. Depending on the situation, an individual may find a preexisting 3D model that someone else designed through popular online repositories such as Thingiverse[1] or create their own using 3D modeling software. There is a wide variety of 3D modeling software created for novices (individuals with little to no formal training) and experts (individuals who commonly have engineering or animation training). Two examples of novice design tools include Tinkercad[2] and Sketchup.[3] Both tools are direct manipulation WYSIWYG (What You See Is What You Get) interfaces that output a standard format (.stl) and are free to use. They offer uncluttered interfaces and objects are built by combining primitive shapes (such as cubes, triangles, and spheres).

[1]http://www.thingiverse.com/.
[2]http://www.tinkercad.com/.
[3]http://www.sketchup.com/.

Table I. Participants Interviewed at Each Site, Listed by Role

| | Instructors | Administrators | OTs | AT Specialists |
|---|---|---|---|---|
| Site A | 3 | 3 | 2 | 2 |
| Site B | 1 | 1 | 0 | 0 |
| Site C | 0 | 0 | 0 | 1 |

Users who have difficulty using on-screen tools may prefer to design models tangibly instead of using on-screen tools. Within the research community, there has been an influx of tangible design tools that enable users to design 3D models by manipulating physical objects. A 3D model is created by 3D scanning these physical objects [Izadi et al. 2011; Follmer et al. 2010], or objects may have embedded electronics that can specify their configuration to the computer [Huang and Eisenberg 2012]. While users can quickly create low-resolution primitives with these systems, their complexity is commonly limited.

Consumer-grade 3D printers are available in a variety of types; one of the most common types used at two of our investigation sites is fused deposition modeling (FDM). These printers heat plastic filament and extrude fine layers of plastic that ultimately create a 3D object. A second type used at our other investigation site is a powder bed printer. This printer combines powder with layers of a binding agent that can be tinted to generate a 3D object in full color.

In our study, we describe challenges and opportunities related to both novice design tools and consumer-grade 3D printers given the state of this technology at the time of our fieldwork.

## 3. DATA GATHERING METHODS

Our investigation set out to gain an understanding of how 3D printing can support special education and therapy. We conducted interviews and observations at three diverse sites: Site A, a special education school serving students with cognitive impairments and multiple disabilities; Site B, a school serving students with visual impairments; and Site C, the technology services department of a national organization working with blind individuals. We conducted long-term classroom observations at Site A and completed a series of interviews with staff, instructors, and therapists at all three sites.

### 3.1. Interviews with Faculty and Staff

We defined a set of stakeholders (Table I) we perceived would be relevant to the introduction of 3D printing in special education. These stakeholders included faculty, staff, and administrators. The stakeholders at Sites A and B give support to students and represent important perspectives in the delivery of curriculum and assistive technology to students in multiple educational settings. At Site C, we spoke with a technology coordinator who provides information to organizations and end-users on assistive technology related to vision impairments.

We recruited participants through email, explaining our research interests and inviting faculty and/or staff to participate. We conducted 13 interviews across three sites (Table I). We conducted individual semistructured interviews lasting 30 to 60 minutes, and all but one was conducted in person and on site. These interviews occurred after we began our observations at Site A and were guided by that data. The interviews were structured around the following themes: software and hardware challenges, student engagement with 3D printing, printer maintenance, safety, intellectual property rights, and time committed to 3D printer use.

We demonstrated 3D-printed objects in the interviews to illustrate the capabilities of current printers (Figure 1). These objects included 3D-printed tactile graphics, small

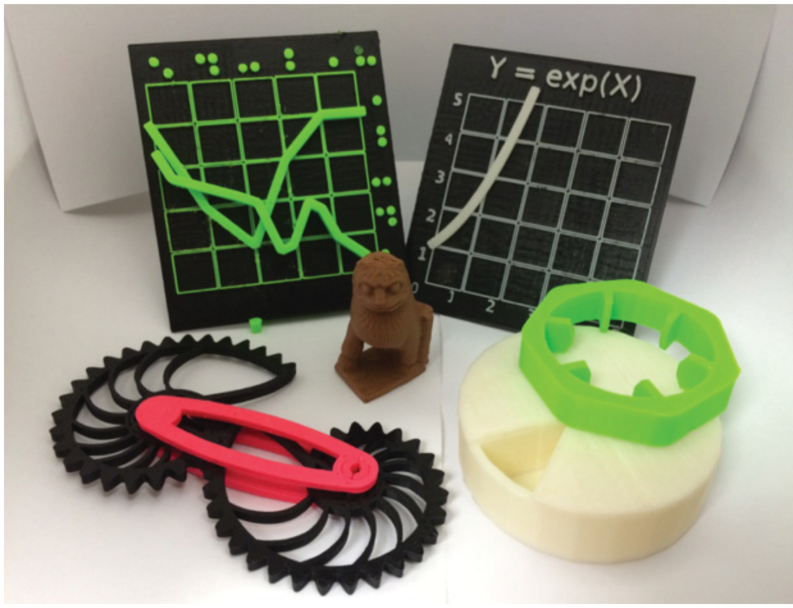



Fig. 1. Examples of 3D-printed objects to support special education. Pictured: tactile graphics for students with visual impairments, a small sculpture and moving nautilus gear for hands-on engagement, and two assistive devices including an easy-grip bottle opener and a pillbox.

models, and working gears. Interview questions and prompts were designed to elicit discussion and further insight on observed themes, but also served to reveal new issues not previously identified. The questions were tailored for the role of the interview participant. For example, we asked technology instructors about the strategies they used to manage student expectations in the classroom; we asked technical experts about failures and successes using the technology; and we asked nontechnical instructors and therapists about their perceptions of and uses for 3D printers in their work setting.

### 3.2. Classroom Observations at Site A

We conducted observations at Site A for one school year while attending six periods of an information technology class each week. This course's curriculum taught computer skills, ranging from office productivity to computer hardware and networking. The instructors and administrators of this school were also interested in incorporating 3D printing into the curriculum. In order to remove obstacles for them to get the printer up and running, our research group provided the classroom with a 3D printer, supplies, and technical support. Our goal was to gather real-world stories about 3D printing in the classroom and remove obstacles that might prevent them from utilizing this technology.

Class sections contained between three and 13 students, two instructors, and one to four student aides, and lasted 45 minutes. Students were grouped by their experience and their support needs from instructors. Thus, students with more experience and lower support needs were placed together, and those students with less experience and greater support needs were grouped separately. We took detailed notes on classroom activities and artifacts such as instruction worksheets, student 3D design files, and 3D printed objects.

### 3.3. Codesign and Prototyping with Occupational Therapists

A development stemming from our observations and other interactions at Site A led to a long-term codesign partnership with some of the occupational therapists (OTs). Together we worked on an assistive device project that went through several iterations of prototyping and evaluation (Section 5). The end product was a hand grip printed to fit a stylus for a specific student with limited hand dexterity. This codesign task was the motivation for a custom design software prototype that we developed and named GripFab.

We conducted a pilot test of GripFab with four OTs at Site A, including the two OTs who participated in the hand-grip design project. The participants were given a crash course in 3D printing technology and given a demonstration of GripFab before being asked a series of questions to gauge their interest in GripFab and its potential applications as design software at their site.

In a follow-up to our pilot study, we completed a focus group with three OTs and an art instructor at Site A, and we demonstrated a revised version of GripFab and brought several printed examples of new hand-grip designs. During the focus group, we asked for feedback on both the software and the new models, and we also used these items to elicit feedback on the important features and software requirements for these participants to engage in 3D modeling and printing techniques.

### 3.4. Data Analysis Techniques

We transcribed and hand-coded observations from field notes. This process entailed two coding passes noting high-level themes associated with the expectations, goals, uses, and challenges related to 3D printing. From this coding, certain themes and stakeholders emerged. These topics were then used to inform a collection of semistructured interview questions to further explore the issues associated with 3D printing in education. Interviews were also transcribed, hand-coded, and finally examined using affinity diagramming. The richness of data gathered from Site A enabled us to split this location into findings that applied in the classroom and findings that applied to therapeutic services on the campus. For the codesign and prototyping sessions with OTs, focus groups were again transcribed and hand-coded. We describe our findings by site (Sections 4, 5, 6, and 7) and stakeholder type (Section 8), describe outcomes from our prototype design software (Section 9), and address common themes and challenges (Section 10).

## 4. SITE A (CLASSROOM): SPECIAL EDUCATION SCHOOL

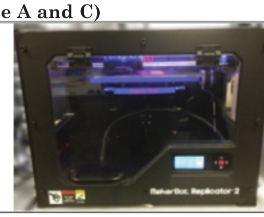
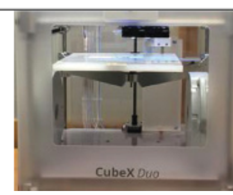
Site A is a special education school that caters to students with moderate to severe cognitive disabilities and, in some cases, multiple disabilities. Students are referred to this school from public schools if they demonstrate a need for additional support services. We focused on a single classroom teaching technology literacy skills.

### 4.1. 3D Printing and Design Resources

This site used a MakerBot Replicator 2x[4] (Table II), on loan from our research lab for the duration of the study. These printers produce objects by additive manufacturing, heating plastic (ABS or PLA) filament. The filament is fed by a stepper motor into a nozzle that extrudes melted plastic onto a heated build plate in progressive layers. The primary design software being used at Site A was Tinkercad, a web-based 3D design tool that is free to use and is designed to support novice users. We suggested this software for its volume of tutorial materials and for its novice-friendly interface.

[4]http://www.makerbot.com/.

Table II. Specifications for the Printers Used at our Sites

| **MakerBot Replicator 2X (Site A and C)** | |
|---|---|
| Approx. Release Price: *US$2,199*<br>Print Speed: *80-100mm/sec*<br>Build Volume: *28.5x15x15.5cm*<br>Print Cost: *$0.01/cc*<br>Material: *ABS or PLA plastic, 2 color* |  |
| **ZPrinter® 450 (Site B)** | |
| Approx. Release Price: *US$40,000*<br>Print Speed: *23mm/hour*<br>Build Volume: *20x25x20cm*<br>Print Cost: *$0.20/cc*<br>Material: *Resin composite powder, multicolor* |  |
| **Cubex Duo (Site C)** | |
| Approx. Release Price: *US$2,999*<br>Print Speed: *15mm/sec*<br>Build Volume: *23x26.5x24cm*<br>Print Cost: *$0.01/cc*<br>Material: *ABS or PLA plastic, 2 color* |  |

### 4.2. Primary Users

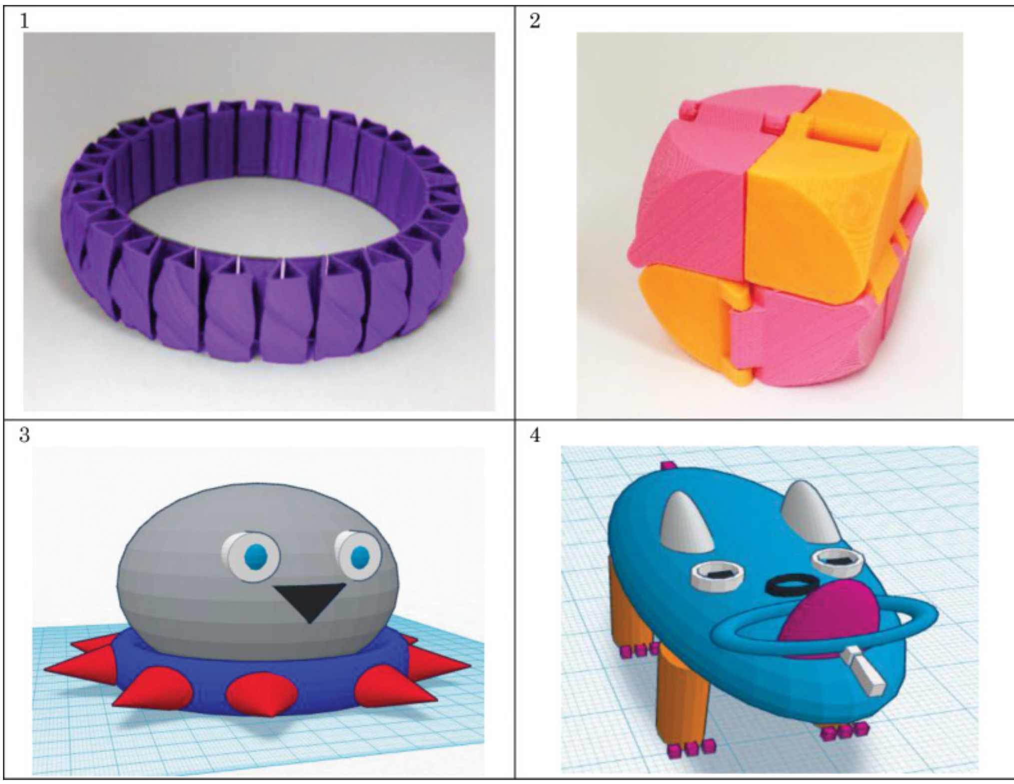
The instructors introduced the students to the concept of 3D printing by showing videos on 3D printing and giving live printing demonstrations in the classroom. The instructors encouraged students to explore existing 3D designs available for viewing, customizing, and downloading from Thingiverse, a 3D printing community that encourages sharing of printable designs. Students selected designs they wanted to see printed before moving on to experimenting with their own designs. Instructors were the most frequent users of the printer and performed all maintenance and troubleshooting tasks, such as starting and stopping prints, filament changes, and printer calibration. We helped instructors when problems arose that they could not resolve, as they had no prior experience with 3D printers before our study.

### 4.3. Use of 3D Printing

Students were given access to Tinkercad and, after completing the website's tutorials (three class periods for some students, more for others), students were encouraged to create their own designs for printing. However, limited curriculum time and difficulty mastering tools prevented most students from finishing custom designs. Instead, students commonly looked for designs from open-source sites to print or modify.

During our observations, the printer was frequently used to produce items for a recurring school fundraiser. The students at this site were encouraged to engage in entrepreneurial activities like creating goods or providing services, and the faculty felt the 3D printer was ideally suited to this exercise. Students selected designs from Thingiverse and the technology instructors printed these designs to sell at a student-run sales event (Table III). These objects were chosen because they were perceived as having universal appeal and would sell at the event. The instructor chose to sell existing designs rather than student designs because they felt the students had not yet mastered the design software.

Table III. Top, Two Items Selected, Downloaded, and Printed by Students for a Fundraiser: (1) a Bracelet and (2) a Cube toy. Bottom, Two Examples of Student-Designed Dog Figurines (3, 4)




### 4.4. Objectives and Obstacles

The technology instructor's ultimate hope was for students to independently design and print objects. The technology instructor wanted to see students use the printer for fundraiser sales or as a type of in-house manufacturing for curriculum aids for teachers outside of the technology classroom. Ideally, other instructors would request that a model or other tactile manipulative be designed and printed by the students, similar to a classroom-based engineering firm. The technology instructors felt this type of experience would provide both STEM engagement and empowerment for their students; however, the progress for these goals has been slow.

Even though Tinkercad is designed for novices, we observed that the students experience several challenges using this software to design new models. Examples include difficulty manipulating camera angle; moving objects instead of adjusting view; confusion about which handles changed scale, rotation, and position of objects; and difficulty selecting multiple objects. These challenges were particularly characteristic of students needing high support. Students could become frustrated and distracted by the interface, and their interest in completing a design appeared to diminish.

In addition to having difficulty using the software, some students had difficulty understanding the physical capabilities of the printer and its materials with respect to their own design concepts. If an object is not positioned on the building plane, this can cause complications during the printing stages either with software being able to prepare the file for the printer or resulting in a failed print. The ability to perceive designs on three planes (x, y, and z) challenged students with high support needs.

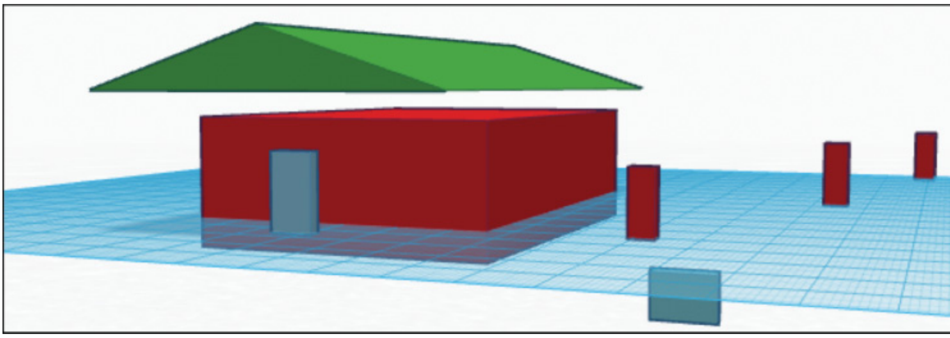


Fig. 2. An example of an unprintable design. This house has a floating roof and is situated below the virtual print bed. Created by a student at Site A.

This resulted in students creating designs that were not seated correctly on the build platform or designs that included object overhangs or details beyond the current capabilities of the printer (Figure 2).

## 5. SITE A (THERAPISTS): SPECIAL EDUCATION SCHOOL

We found that other support staff at Site A were also interested in the 3D printer, and this section describes how OTs wanted to use this technology.

### 5.1. Printing Resources

Once we introduced the OTs to the 3D printer and explained its capabilities, they saw many opportunities for the technology in their work, including modifying or replacing basic AT items like accessible clasps, custom technology cases, or novel designs. We assisted therapists in the design and printing of a 3D object as a prototype for an AT design to encourage the therapists' exploration of this technology.

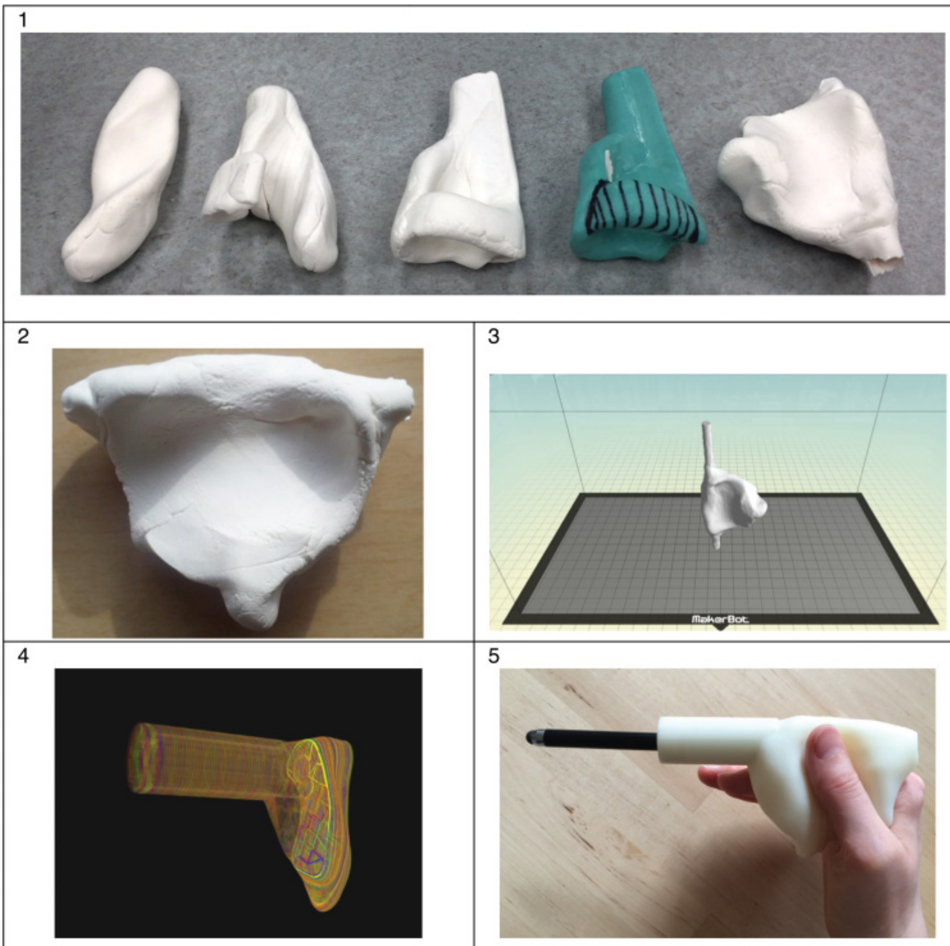
The therapists had access to the same MakerBot Replicator 2x in the instructional classroom, but none of them chose to use the device directly due to time constraints and training needs. Instead, we worked closely with them on the design and manufacturing of custom objects. This group was interested in scanning physical models made from clay, so we provided a MakerBot Digitizer[5] (a 3D scanner that combines images of a physical object and converts this to a closed 3D object for printing). We refined and modified these models using a combination of open-source software, including Tinkercad, MeshMixer,[6] and Autodesk 123D.[7]

### 5.2. Primary Users

The OTs at Site A provided therapy to a diverse student population. Sessions lasted for the duration of a class period (45 minutes) and often incorporated skills practice or other specialized therapeutic routines for students. The therapists did not feel they had the time or skills to commit to working with the printer directly, but described their existing practices for modifying AT devices or creating new ones mostly through the use of quick-fix supplies like Velcro, tape, string, paper, cardboard, and so on. We felt we could translate these practices to low-fi prototyping and assisted two OTs with the technology to create a final product.

[5] http://store.makerbot.com/digitizer/.
[6] http://www.meshmixer.com/.
[7] http://www.123dapp.com/design/.

Table IV. The Adaptive Stylus Grip Went Through Several Design Iterations. Pictured: (1) Initial Air-Dry Clay Models and an Early 3D-Printed Prototype of the Student's Grip, (2) the Final Low-fi Clay Design; (3) Scanning the Clay Model with the Digitizer, (4) Designing an Extension to Accommodate a New Stylus, and (5) Final 3D-Printed Grip with Stylus Inserted




### 5.3. Use of 3D Printing

At Site A, we collaborated on a 3D-printed assistive technology project with two of the school's OTs. We saw this case study as an opportunity to find out what these therapists could be doing with the printer, if given the right resources. The goal was to create a unique stylus grip for a student with a limited grasp. The OTs had previously tested over $150 worth of assistive and mainstream off-the-shelf stylus and stylus-like products but found no satisfactory solution.

Prior to our design activity, the student was using the eraser tip of a pencil combined with a soft gel grip, but this did not meet the exact needs of the student and sometimes caused discomfort or fatigue. In order to create a custom device, we agreed it would be best to create a new design shaped to fit the student's hand and that the device could be 3D printed.

This grip was designed through three iterative rapid prototyping sessions (Table IV). The OTs created initial prototypes using lightweight, air-dried clay to form a base model of the student's grip, which was then 3D scanned by the researchers using the Digitizer. Adjustments were made to the design to accommodate a basic stylus and the design was printed using a Replicator 2x located in our lab. The plastic prototype was delivered to the OTs, who conducted test sessions with the student. During testing, concerns were raised about the hardness of the plastic. Our lab coated the grip in a rubberizing aerosol spray to soften the texture and improve grasping. Both the new texture and the bright color (picked by the student) were well received. The student later purchased a different stylus and the task of modifying the grip prompted us to explore other design options that we discuss in our software prototyping, in Section 9.

### 5.4. Objectives and Obstacles

Therapists from Site A were excited at the prospects of 3D printing and were considering other individualized devices to create in the future. However, they currently see the task of 3D design and printing to be someone else's work, and see themselves as consumers of that work. For these participants, 3D printing is largely meeting their expectations because the design and test print processes are being obscured from them.

The OTs were interested in learning how to design and create 3D prints, but were concerned about the required time commitments and learning curve to familiarize themselves with the software. "I wasn't sure how much was involved in the [design and printing] process; it seemed like a lot of work" (OT, Site A). Each therapist works with multiple students and has limited time with each student. Their interest was piqued by the prospects of the 3D scanner used in the grip project, but because the grip needed to be altered to correctly hold the stylus, the OTs again perceived the time to design and implement these modifications as outside of their capacity.

## 6. SITE B: PRIVATE SCHOOL FOR BLIND AND VISION-IMPAIRED STUDENTS

Site B is a private organization that provides programs and resources for students who are blind or vision impaired between the ages of 3 and 21. Some students have multiple disabilities. The 3D printer at this site is located in a technology classroom.

### 6.1. Printing Resources

The 3D printer at this site is a ZPrinter 450[8] resin composite machine. This printer and most of its materials were donated to the school at no cost. Resin composite printers have a slightly different printing method from the printers discussed so far. In this printing process, the layers are created by sealing together resin powder with a binding agent, enabling for higher-resolution, full-color prints (Table II).

For designing, Site B used Rhinoceros 3D,[9] which includes both a mouse-driven interface with more advanced tools than those found in Tinkercad and a command-line-driven design mode, where students can supply programming commands to draw shapes. Rhinoceros is a tool for experts with a very different learning curve from open-source tools like Tinkercad and has a high cost ($1,695). This software was chosen for its command-line accessibility and supporting tutorials.

### 6.2. Primary Users

At the time of our interview, the school's technology instructor had been the primary user of this printer, owing to the need to gain familiarity with the software and incorporate the printer into future curriculum. A small group of students had tried the

[8]http://www.3dsystems.com/.
[9]http://www.rhino3d.com/.

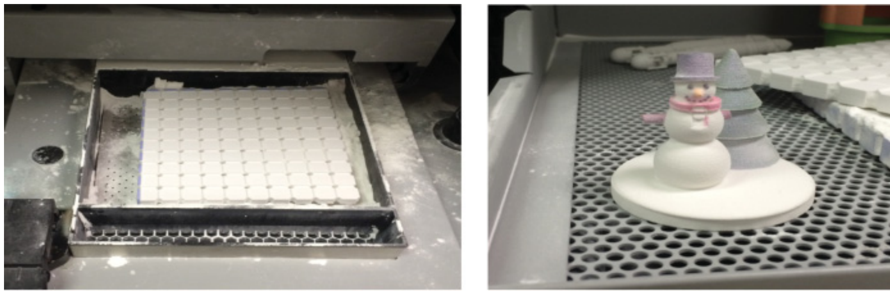


Fig. 3. Example objects printed at Site B. On the left is a math manipulative project aimed at creating a tactile Cartesian grid. On the right is a decorative snowman figurine designed by students.

printer and software as part of an extracurricular activity. The instructor has plans to create and implement lessons for the students in his class in the future.

### 6.3. Use of 3D Printing

This site had the printer for 1 year and printed few objects (10 to 20). Example designs include a snowman figurine and a geometry manipulative (Figure 3), both created with Rhinoceros 3D. The technology instructor at Site B received a request to create a geometry manipulative that would allow visually impaired students to tactilely interact with their math curriculum. Three students from the technology class created the snowman figurine as part of a software tutorial.

### 6.4. Objectives and Obstacles

Similar to Site A, this site's goal is to teach students enough skills for them to become independent 3D designers, and the instructor had concerns about the students' ability to master the modeling software. Specifically, they were concerned that the planned 3D modeling curriculum might prove a challenge for the vision-impaired and blind students. The instructor anticipated struggles to fully grasping command-line-based design and issues relating to the build plate and design symmetry. The printer at this site required very delicate calibration including tasks that bordered on the impossible for students, such as using a mirror to make adjustments to components underneath and/or deep inside the machine.

Another goal at this site was to provide tactile graphics and other manipulatives to students and teachers. Unfortunately, the durability of prints made by this type of 3D printer was an issue, as objects that come from this printer may not be strong enough to endure extensive handling. The resin composite prints are very fragile when they first come out of the print bed. Thick or large objects are often heavy and can easily break during the final stages of vacuuming off excess powder before applying a final coat of resin for strength. Additionally, after constant handling, prints can still crumble or crack, and gluing them back together is not always successful. This is a serious issue for a population that relies heavily on touch and needs durable prints.

## 7. SITE C: TECHNOLOGY CENTER

Site C is the technology center within a national organization that provides advocacy and training for individuals with vision impairments. At this location, we interviewed an assistive technology expert about the exploration and promotion of 3D printing as a tool for tactile graphics and supporting alternative access to educational materials, such as hand-held models.

### 7.1. Printing Resources

Site C currently employs two plastic extrusion printers, a MakerBot Replicator and a Cubex Duo[10] (Table II). While other sites focused primarily on the cost or convenience of a 3D printer when deciding on which model to acquire, this site also focused on customer support. The technology expert from this site pointed out that many consumer-grade printer manufacturers are small companies with limited technical support, static FAQs, or forums that aren't always accessible. Having a live person to call up and ask for troubleshooting assistance makes a difference for end-users with visual impairments.

This site uses open-source software wherever possible, including Tinkercad and 123D Design. Other resources, such as Thingiverse.com and GrabCAD[11] (an open engineering group offering free tools and model-sharing communities), are used to find existing models.

### 7.2. Primary User

At Site C, we spoke with a technology expert who provides information about and training on assistive technology tools related to visual impairment. This expert is the primary user for this site's two 3D printers and is self-taught in CAD design and 3D printing. As part of a small department serving a large population, this participant leverages 3D printing only when other options are not practical and is the sole user at this site.

### 7.3. Use of 3D Printing

The printers at this site are used for demonstrations, training, and support material for events put on by the organization. When individuals or groups contact Site C for information on 3D printing, the technical expert can provide the seeker with information on types of printers, hardware costs, software suggestions, and ideas on how 3D printers can be used to support visual impairment. This primarily includes tactile graphics and models to support access to information. Due to time and ability constraints, printed designs are roughly an 80–20 split between open-source designs and creating novel designs. Figure 4 illustrates some of the models that have been printed at this site.

### 7.4. Objectives and Obstacles

This site's current goals for the 3D printer are to create tactile graphics and hand-held models and provide information for other individuals or organizations that would like to know more about using 3D printing in support of visual impairments. However, our participant mentioned the tedious and time-consuming task of mastering CAD. They also described serious issues regarding support for users.

"For something that's supposed to be consumer-grade, that's just not workable. Their support is good, but for some things I have to wait three days for a response!" (Tech. Expert, Site C). Other possibilities, such as 3D scanners, are perceived as promising ideas, but likely not as practical as advertised. "I'm very wary because I feel like so much of it is marketed as, 'Oh it will scan and you'll get a print-ready model' and I'm very skeptical of that" (Tech. Expert, Site C).

## 8. 3D PRINTING STAKEHOLDERS IN SPECIAL EDUCATION

Stakeholders were identified based on in-class observations and on the structure of the different sites utilizing 3D printers. We recognize that this is by no means a complete list of stakeholders. In particular, we acknowledge that parents, other caregivers

[10] http://www.cubify.com/.
[11] http://www.grabcad.com/.

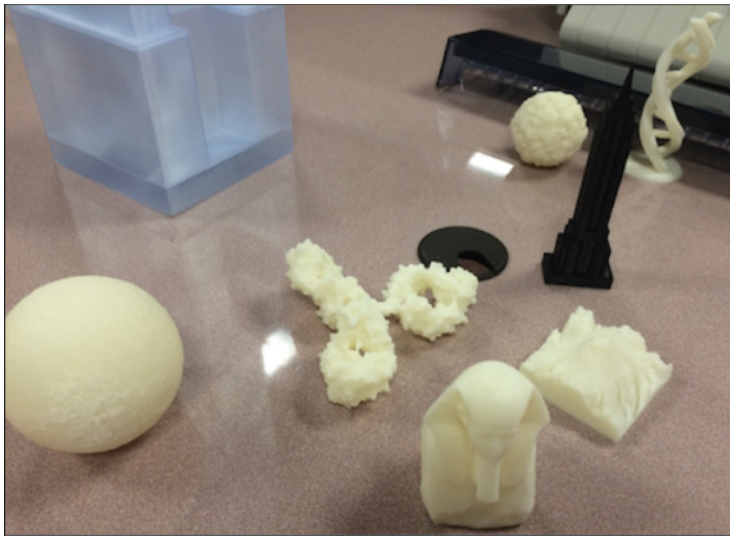


Fig. 4. Models printed at Site C to support information access for visually impaired users. Pictured: a planet, the Sphinx, the Chrysler building, a DNA helix, & a landmass.

outside of the school setting, and the children themselves should be involved in this research. For this study, we had to exclude these populations for reasons of access and other constraints that are discussed in Section 10.5. Instead, we are focusing on the faculty and staff providing education and access to tools such as 3D printers, in addition to leveraging these tools themselves as a means of contributing to the quality of life and education for their students. To follow, we provide a brief description of each stakeholder group and their high-level reflections on 3D printing technology in special education settings.

### 8.1. Administrators' Perceptions and Expectations

Administrators include those involved in management of personnel, curriculum design, and/or site planning. This group had little to no hands-on experience with 3D printing but was often involved in deciding how or why a 3D printer was added to their location. They shared high-level thoughts about safety, reliability, and educational outcomes for 3D printing. Overall, they perceived printers as safe to use with supervision. Their only concerns were related to safety regulations and standards for equipment, but they felt that printers were well within the guidelines they already had in place. One administrator pointed out that the school had a cooking class and felt an oven was equally or more dangerous than a 3D printer. This perception could indicate a lack of understanding, as most printers have parts that heat up to temperatures much higher than a conventional oven. The administrators' lack of experience with the printers may be coloring their expectations and the needs of the employees they supervise.

We interviewed four administrators (two assistant principals, one vice principal, and one curriculum director). These stakeholders had the least interaction with students and also the highest expectations of what students could do with a 3D printer. Administrators described optimistic scenarios in which students would have the ability to design and produce custom objects with ease, providing design and print services to other parts of the school campus and even to the local community. These administrators were interested in students making both educational aids and assistive objects. "[3D printed AT] is the thing that's going to revolutionize care for people. Truly individualized solutions" (Admin., Site A). In addition to creating low-cost AT solutions and classroom manipulatives, they perceived this technology as affording students with employability skills and as a means of practicing math and engineering. An administrator at Site A suggested that 3D modeling and printing "...presents engineering in a manageable way" and went on to explain that the student body "...deals best with hands-on approaches to learning."

While some administrators understood the time constraints of 3D printing, few had concerns about the amount of time necessary for students or staff to learn 3D design and printing tools. They described a need for training or workshops for faculty in order to spread awareness of what 3D printers could do and to discuss the best classroom to host printers. Administrators were interested in a catalog where staff members could choose from an existing set of objects for their classrooms or place special requests that the students learning 3D printing would design and fulfill.

### 8.2. Occupational Therapists' Perceptions and Expectations

Our investigation sites offered different services to students (depending on student need and resources) including therapy. We initially interviewed two occupational therapists at Site A, and later we returned to this site and got feedback from three additional OTs as part of our GripFab study. General feedback we received about 3D printers from all OTs is included in this section. These participants had limited exposure to 3D printing, and their knowledge of printers came from recent media coverage on printers or from local sources such as other staff members, friends, or family who told them about the technology.

This stakeholder population offered potential applications for 3D printers creating adaptive or assistive devices both for therapy sessions and everyday interactions. Objects they considered for 3D printing included the grips we explored in our design case study, modifications to devices and AT such as cases and screen guards, and specialized fidgets (small objects with textures and/or articulated components that can be "fidgeted" with) for students with sensory and attention needs. They were particularly keen on the idea of customizing objects for their students: "...because it can be customized it opens the door to these things [individualized solutions]." The OTs felt there were likely more applications, but that they would need time and exposure to the printer before they were able to realize more possibilities. Therapists also gave us more information on the costs of customized AT and potential safety concerns for 3D printed objects in this context.

Therapists at this site indicated that their biggest concern with 3D printing was the time investment to learn the design skills and software tools to create novel 3D-printed objects. At the onset of our interviews, the OTs were unfamiliar with the time needed to create medium and large prints. "[I] thought I could go to someone and say, 'Hey I need this,' and they could print it in 15 minutes...." After we described the time constraints on these prints, the OTs agreed that a 3D printer was still a useful tool. However, they wanted to reduce the trial and error of their designs as much as possible and felt that this level of design efficiency would only come with mastery of 3D modeling tools. This brought the conversation back to their own time constraints working with a large student population.

These participants had very few safety concerns about the use of the printer or of 3D-printed objects. They cited existing protocols for testing and vetting any new piece of assistive or adaptive technology and the close observation of students already in place at a special education school. The OTs agreed with administrators about the need for workshops or training for faculty to help promote understanding and brainstorming about the use of 3D printers in their schools. They indicated that 3D-printed solutions to accessibility challenges would be considerably less expensive. Therapists were interested in alternative materials for 3D-printed objects, including soft textiles and rubber- or foam-based filaments to create easy-to-grip or flexible objects.

### 8.3. Technology Instructors' Perceptions and Expectations

This group represented the primary point of contact with the 3D printers at each location. These stakeholders are most versed in the design, printing, and maintenance processes. Instructors provided their war stories about printing in an educational setting. This group spoke to challenges for youth in the design and printing process, as well as the shortcomings of the software and hardware involved, and shared their ideas for improvements and new uses for the printers. This helped us juxtapose the desires of the other stakeholders versus the realities of the technology, particularly in the case of stakeholders who were far removed from the printing process, such as the administrators.

We interviewed three technology instructors, two from Site A and one from Site B. These participants shared several challenges related to teaching 3D printing in a special education classroom. These stakeholders identified time management, software complexity, and hardware reliability as serious obstacles to successful 3D printing curriculum. Technology instructors indicated that they did not have enough time as educators to master 3D design and print technologies and that they also struggled to create enough time for 3D printing in their existing, packed technology curriculums. They described steep learning curves for their students when teaching 3D modeling software, student difficulties using mouse-driven design interfaces, and problems managing expectations and maintaining student motivation during the design process.

The instructors at Site A struggled with persistent hardware failures that impacted instructor and student morale and engagement with the technology. The students at Site A are most familiar with procedural education where scheduling and task completion are an important part of the learning environment. The instructors stated that printer failures or struggles with the design software were very disruptive: "We do A, B happens, and C is what you get. With everything they do. If that doesn't happen, you lose them" (Tech. Instructor). While we were able to supply a more reliable printer, the instructors continued to manage student expectations.

### 8.4. Nontechnology Instructors' Perceptions and Expectations

Two of our investigation sites offered academic courses, including classes on history, art, mathematics, music, and so forth. We interviewed one nontechnology instructor at Site A. Our goal was to identify perceptions of 3D printing and to discover alternative uses for the printers not currently being explored at the investigation sites. This instructor taught art but had a very antitechnology stance for his classroom.

The art instructor described admiration for 3D printing and similar technologies, but stated that he preferred hand-crafted arts and his only interest in 3D printing for his classroom was an alternative means of sculpting or painting during his three-dimensional art unit. "They always use computers at home. In here [art class room], I want them to get an experience they don't get at home. Hammers, chisels, other tools. I don't want them to use the computers" (Nontech. Instructor, Site A). Despite interfaces that use scanners to transform literal hand-made 3D objects into digital designs or modeling software that provides users with the metaphor of a clay block to be directly manipulated, this instructor insisted that 3D printed objects were not part of his traditional definition of three-dimensional art. A single instructor is not representative of all nontechnical teachers; however, the example highlights that not all educators are interested in this technology.

### 8.5. Technology Specialists' Perceptions and Expectations

Technology specialists at investigation Site A provided support to their colleagues and to students. The specialists at Site A had a cursory knowledge of 3D printing, but they were not the primary users at their site. At Site C, the technology specialist was the primary user and assistive technology expert. By supporting special education needs via technology, these stakeholders regularly evaluated and informed the applied use of a variety of assistive technology solutions. They gave insights into costs, alternatives, and appropriate deployment for 3D printer technology.

We interviewed three assistive and information technology specialists. Their perception and interest in 3D printing aligned with the therapists at Site A. Like the therapists, they had few worries about the safety of 3D printers and instead were concerned with the time and personnel needed to operate it. Unlike administrators, the specialists at Site A did not necessarily see students as the lead designers of AT devices. They saw, instead, a specialized position somewhere between AT and OT in which an individual or a team was dedicated to creating assistive solutions with the printer. The specialist at Site C echoed similar thoughts, describing a high time commitment and a need to have at least one person at any institute trained explicitly and extensively on how to use the printers and 3D modeling software.

This group indicated that 3D printed assistive solutions would be a tremendous cost savings over existing products. "There's a lot of assistive technology that's so expensive—it's so expensive! And it's because it's such a niche—a super niche market. Even something as simple as an adaptive penholder is going to be ridiculously expensive. [I see] a lot of potential for the 3D printer to come in and create these things that people could use for much cheaper" (Tech. Specialist, Site A). They also wanted more variety in printable materials to support a range of AT products, including mixed materials, textiles, rubber, and metal. One specialist who works mostly in AT described the struggles of making individualized AT devices. "How [to] customize something when the standard isn't appropriate for a particular person? ... We do try to make them [custom AT] and making them takes time" (AT Specialist, Site A).

In addition to using the printer to create AT objects, these participants identified the printer as a way to support UDL by creating difficult-to-find, nonexistent, or costly educational aids and manipulatives. They also described a need for more open-source designs of such objects. Similar to other stakeholders, these specialists favored a collective set of designs made available freely to educators and care providers to more easily create and print AT and UDL objects in 3D.

## 9. DESIGNING ASSISTIVE TECHNOLOGY 3D MODELING SOFTWARE FOR THERAPISTS

After working closely with the OTs at Site A through interviews and the codesign of a novel stylus grip for their students, we developed a prototype 3D modeling software to enable them to easily create 3D-printed accessible hand grips. In this section, we describe the motivation, initial requirements gathering, and findings from demonstrations and focus groups of this software with additional OTs at Site A.

### 9.1. Need for Customized 3D Modeling Software

As described in Section 5, we worked in cooperation with two OTs to create a 3D-printed customized stylus grip for a student. Our grip design fit the student's hand and stylus well and was considered a success. However, the student found that the stylus itself was not as responsive to her touchscreen device and purchased a new and larger stylus that did not fit our grip. The OTs asked us if it would be possible to modify the grip design to accommodate this new stylus. This request highlighted the common problem that many AT devices are outgrown or require changes or updates to keep pace with changing electronics. Other examples of changing AT needs provided by OTs included students breaking devices or cases and student families purchasing new devices requiring new cases, mounting, and so forth.

The OTs made it clear to us that more requests like this one were likely, and we needed to provide a design tool that would empower them to build other custom devices. Given the OTs' reticence to spend time learning existing software, we needed a solution to quickly and easily create variations on designs to accommodate change.

### 9.2. Requirements for 3D Modeling Software for Special Education Settings

From our interviews and design work with the OTs, we came up with a basic set of requirements for a minimal design tool. Even though the hand grip was explicitly created for one student, the therapists indicated that multiple students could benefit from a custom grip modification for an array of objects. We designed GripFab, a simplified design tool for generating customizable hand grips. In our initial conversations with OTs, we recognized that we needed to create an interface that would (1) minimize time commitment, (2) offer simple customization without mouse-driven design to improve model accuracy, and (3) obscure as much complexity as possible to mitigate the intimidation factor associated with CAD modeling tools.

*9.2.1. GripFab Features.* To fulfill the aforementioned requirements, we abstracted 3D model generation down to parametric fields and option-selection settings. GripFab uses a tabbed interface to break up the design process emulating a step-by-step wizard. This forces the user to consider sections of their grip separately and limits the overwhelming number of options available to the user. Each tab offers the user a small set of options related to each feature of the hand grip: (1) selecting the base shape, (2) adjusting the dimensions of the hole in the grip accommodating the object to be held, and (3) optional support called a "barrel" that can be used for holding longer objects or to provide an extension for a user with limited range of motion. GripFab combines Java and an open-source, console-based design tool called OpenSCA[12] to apply the designer's settings and render a model as an .stl file. All necessary files for rendering are saved locally and then removed once the .stl is fully rendered. This interface masks the rendering process from the user, leaving a clean .stl file for printing.

*9.2.2. GripFab Version 1 - Pilot Study Feedback.* We pilot tested the first version of GripFab in an hour-long focus group at Site A with four OTs, including the two involved in the original hand-grip design project. The session included a brief demonstration that was followed by a set of semistructured questions regarding the OTs' experiences with hand motor impairments and their current practices for devising solutions for accessibility challenges. Participants were shown an example grip designed to hold a spoon (Figure 5) and asked to make a grip design for a large highlighter using GripFab. One participant controlled the software while the other three provided feedback on the usability of the application.

The OTs gave favorable reviews of the software and grips and provided us with a list of improvements. To minimize the time commitment, the OTs requested a profile system that would load default values about a student (e.g., left- or right-handed). They requested dynamic images to help visualize the models, but they did not want to use these images for direct manipulations of models. For the software, they requested parametric field and tool labels with more OT-friendly language to help alleviate confusion over CAD vocabulary. The OTs also described a need for more diverse base grip shapes and provided us with a set of art supplies spanning several shapes and dimensions, including pencils, markers, paintbrushes, glue sticks, and other supplies.

[12]http://www.openscad.org/.

Fig. 5. A 3D printed assistive hand grip for a spoon.

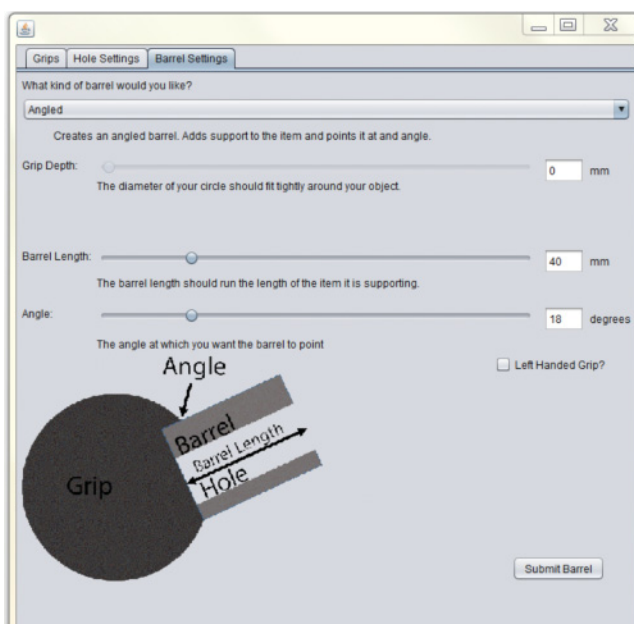
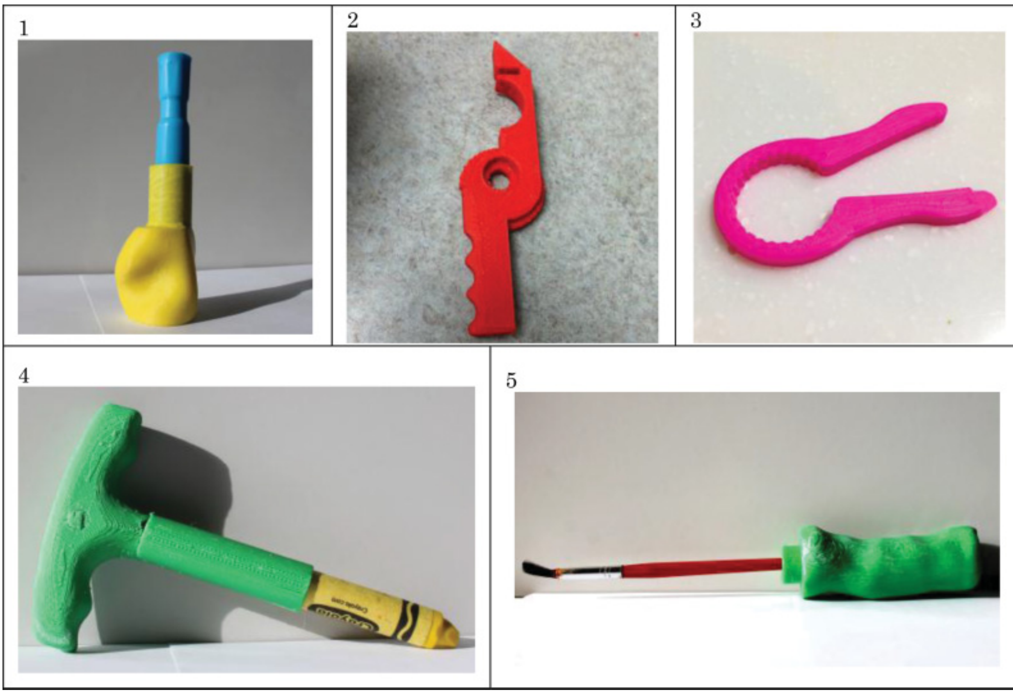



Fig. 6. Screenshot of GripFab showing variables related to accessory width.

*9.2.3. GripFab Version 2 - Focus Group 1 Feedback.* We implemented a few changes to GripFab and also created several potential base grip designs to accommodate the art supplies provided to us at the end of pilot testing at Site A. Changes to GripFab included the incorporation of two new base models and the ability to angle the barrel support (Figure 6). The new printed hand grips were a mixture of novel designs based on needs described by the OTs in the pilot study and modifications of existing designs from AT catalogs and Thingiverse. We conducted an official focus group with three OTs and one art teacher, including two OTs from the pilot study.

Again, we saw emphasis on time savings, simplifying complex design techniques, and obscuring complexity. Even though the OTs praised the step-by-step process of

Table V. Top Five Grip Designs as Selected by OT and Art Faculty at Site A: (1) Refined Pinch Holding a Highlighter, (2) Articulated Container Grip, (3) Bottle Grip, (4) Rocker Grip Holding a Large Crayon, and (5) Built-Up Grip Holding a Thin Paintbrush




creating grips, they suggested providing a tutorial to help guide them through the design process. They also requested new features, such as the ability to change the scale of the base model and increase/decrease the width, length, and/or overall size of the base grip to provide more flexibility and customization of the grips. Previously, the ability to scale or stretch a design has been controlled during the slicing step between generating the 3D model and preparing it to print. By reducing the number of programs they must interact with, the OTs are again looking to reduce complexity even though this is adding in more features to the design interface. Concerned about the print time necessary to create several variations of a grip, the OTs also wanted the option to print alternative interlocking barrels on preexisting grips. Ideally, they would have a base model that fit a particular student's need and they would print hot-swap barrels to accommodate all the different hand implements the student interacted with during the school day.

### 9.3. Utility of 3D-Printed Assistive Grips

In addition to learning about the requirements of design software, we also identified high-level feedback on creating assistive hand grips. In our second and final official focus group, we brought 12 different grip base designs ranging from bases modeled after household tools like screwdrivers, existing grasping tools sold by AT manufacturers, and grip designs found on Thingiverse. We asked the OTs to evaluate the usefulness of each grip model and whether or not it would make a beneficial addition to the base model library in GripFab.

The five grips the OTs described as most useful were the *rocker*, *refined pinch*, *built-up*, *articulated container* grip, and *bottle* grip (Table V). The attributes of these grips gave the user flexibility, a steady comfortable grasp, and mobility support. The *refined pinch* is a generalized version of the custom grip design we created for the student in our codesign project. The *articulated container* grip was made explicitly for the operation of a glue stick. The grip clasps around the glue stick, providing the user with the ability to turn the glue stick upside down, sideways, and upward. The *bottle* grip is an existing design available on Thingiverse [Minifacture 2013] that we selected for thicker objects and containers found in the art classroom, specifically a small bottle containing glitter. The *rocker* grip is a T-shaped grip based on existing AT designs for persons who have some grasping ability but only lateral wrist movement. A *built-up* grip is an exaggerated handle based on a technique described by the OTs wherein they wrap material around nonassistive handles to make them easier to grasp for people with limited dexterity.

The OTs preferred to have generalized grips over user-specific ones, a default average adult hand size, and the ability to attach extra support materials to the grips to give the user more stability when interacting with objects. For instance, the extra support material would allow them to take the lid off the jar, hold it, and pour with stability. The OTs stated that they would like to use GripFab and a 3D printer in their daily practice if we can incorporate the remaining feedback on the interface and add these five designs as base models. They described a 2-week waiting period for ordering and receiving AT products from catalogs and manufacturers, suggesting that 3D-printed options would save them wait time. The OTs also said that based on their understanding of 3D printer material costs, using 3D-printed grips would also be more cost effective.

### 9.4. Implications for Self-Designed Assistive Technology and Disruptive Service Delivery

GripFab is one example in a movement toward self-designed assistive technologies. To a certain extent, customization has always been a component of AT design. Therapists and end-users regularly make low- and medium-fidelity modifications to AT by incorporating tape, clay, cardboard, Velcro, and other artifacts to improve the fit and utility of off-the-shelf solutions. Not all people with disabilities have the level of motor ability and dexterity necessary to make use of these materials. At the same time, contemporary design tools also have barriers to access, relying heavily on mouse-driven techniques and requiring training in CAD to generate novel designs in 3D. Tools like GripFab or the Thingiverse Customizer are part of an emergent toolset that supports designers who can access a computer. Our findings indicate that the use of parametric settings may enable a wider user population to create bespoke AT objects, but we have not yet completed extensive testing to discern which populations will benefit most from this practice and if this modality is the best option over other modalities for specific user abilities and level of design skills.

This accessible self-design concept does not need to be limited to 3D printing. Instead, we propose that the new model for manufacturing be made more inclusive by way of accessible fabrication tools. With the creation of accessible fabrication, we can support and promote end-user self-design of AT. When combined with the user's constructionist learning from the use and design of these items, this creates a disruption to existing service delivery and service design. We, as HCI researchers, can then foster collaboration between end-users and clinicians in the creation of novel or custom AT. By empowering the end-user as a designer of his or her own AT solutions, we can also incite engagement, leading to better adoption and reduced abandonment rates.

## 10. DISCUSSION

These studies reveal that there is support and interest in using 3D printing in special education and therapy. Through this work, we identified several recommendations for technologists related to the development of 3D hardware and software, we identified issues of interest to schools and therapists, and we provide our lessons learned studying 3D printing technology in special education settings.

### 10.1. 3D Printer Accessibility Recommendations

We believe it is important that the 3D printer be considered as an assistive technology in the special education classroom and not simply another piece of technology. We make the following recommendations specific to this cause.

*10.1.1. Provide Accessible Feedback.* One significant obstacle we observed for novices learning to use this technology was developing an accurate mental model of the printer. Common problems included not understanding why prints failed, the limits of a given printer's capabilities, and the relationships between troubleshooting techniques and the problems they are intended to solve. As we move toward a future where students with diverse abilities use these printers, it is important to provide accessible feedback about when the printer is working and when there are problems.

*10.1.2. Printer Safety.* 3D printers can be dangerous when misused. While we did not see specific concerns from any of our stakeholders about the safety of these machines for students, it should be considered for future audiences. All of the 3D printers our participants interacted with had enclosed all hot and/or moving parts, so they would be difficult to touch while the printer was on. Additionally, students at these sites are monitored very closely, and the administrators felt that it was the teacher's responsibility to keep students safe.

*10.1.3. Offer Appropriate Customer Support.* Given that 3D printing is not yet as robust as other consumer technology, it is important to provide consumers with appropriate support. While this is true for all end-users, it is particularly true for assistive technologies where end-users are accustomed to having access to experts, technical support, and repairs. This was made clear to us in our interview at Site C, where purchasing decisions were informed based on available support.

### 10.2. 3D Modeling Accessibility Recommendations

*10.2.1. Make Accessible Software.* As 3D printing becomes more common, 3D modeling software must be accessible. Specifically, this software must support screen readers, switch input, and other common computer access customizations. According to our participant at Site C, there is currently no open-source 3D modeling software that is accessible to a screen reader. The accessibility of these tools should also be considered for end-users who have difficulty remembering complex task sequences or have limited short-term memory.

We suggest GripFab as one example created toward increased accessibility. The OTs found contemporary CAD tools to be inaccessible based on their skillsets and time affordances. By identifying design needs and discussing interface options, we were able to create a single-purpose program that enables the OTs to create and modify 3D models without extensive training or CAD experience. This is not to say that technologists should create a single design tool for every special case of 3D printing, but instead provide guidelines for identifying needs and skills of special designer populations and working with those individuals to arrive at more approachable software.

*10.2.2. Consider the Learning Curve.* It would also be prudent to explicitly design 3D modeling software to support a range of expertise and to support the transition from novice to expert performance. While many of our participants were excited to use 3D printing, most found the current 3D modeling software intimidating. For these users, novice tools don't provide enough control, but expert tools come at too high of a cost in terms of outright expense, learning, and time investment. Adding optional features to support novices such as detecting unprintable designs and integrating tutorials into the modeling software might assist users when they are struggling.

*10.2.3. Encourage Sharing of Existing Models.* Not all end-users want to create custom designs, and it is often enough to make minor tweaks to existing object models. Faculty who were not directly involved in teaching technical topics felt they would be more comfortable using a catalog of existing items, similar to Thingiverse.com, rather than learning CAD. This concept was echoed by administrators at Site A, who felt that a central repository of tools, designs, and support would be the best fit for the teaching faculty not currently involved with the 3D printer. Several participants wanted curriculum support, such as miniature models or student-tailored objects that could be selected from a list and printed on demand.

*10.2.4. Support Editing Existing Models.* A mix of existing 3D modeling tools or minor modifications to existing tools may be enough to support some of the stakeholders discussed in this article. While we are starting to see customizable 3D models (such as Customizer on Thingiverse), these tools are limited. 3D scanning physical objects may offer an easier way to create custom designs; however, many current 3D scanners have low resolution or require complex cleanup to make a printable model.

### 10.3. Recommendations for Special Education and Accessibility Organizations

We saw a range of exposure, comprehension, and skills related to 3D printing that impacts decisions about choosing appropriate tools for modeling and printing. To accommodate this, we recommend carefully surveying the skills and application goals of users before choosing a printer or set of modeling tools.

*10.3.1. Budget Time for Training.* Participants with 3D printing experience expressed concerns about the time necessary to train themselves, other staff, or students to create novel 3D designs. They feared mastering these tools would take days, weeks, or even months. This is concerning given that our participants consider learning 3D printing as “extracurricular” and not what they were explicitly hired to do.

*10.3.2. Consider Printer Reliability and Maintenance.* As is a common complaint with the recent 3D printing boom, there are serious setbacks in the consistency and quality of printer performance [Lutz 2013]. These shortcomings include maintenance, troubleshooting, and unanticipated poor-quality print outcomes.

These issues are crucial for accessibility and education applications. For example, when making custom-fitted assistive devices, precision is key to successfully replicating details or measurements. When teaching 3D design and prototyping to students in special education, consistency and reliability impact the learning experience. Students with visual or cognitive impairments may already endure obstacles to accessing the design and modeling end of 3D printing; adding the complexity of unreliable print output is an additional discouraging factor.

*10.3.3. Develop a Plan to Share Resources Equally.* The placement of a 3D printer in a school is important and impacts who will use it. We believe that since the 3D printer at Site A was physically located in the technology classroom, the therapists were more hesitant to use it than if it had been placed in their space. As pointed out by the technology instructors at this site, the students are sensitive to disruptions in daily classroom activities. Having the printer running on a nonprinter day could distract students from their other learning goals. This, combined with the amount of time needed to print medium to large objects, hindered the OTs’ ability to use the printer in the classroom. As the market of consumer 3D printers under $500 continues to grow, it may make sense for educators to invest in multiple inexpensive printers rather than one high-end printer. This would enable higher production rates for printed objects and reduce conflicts of use like those described between the OTs and the technology classroom.

### 10.4. Recommendations for Therapists

*10.4.1. 3D Printing Custom-Fit Objects Is Possible.* Our design sessions with Site A's OTs demonstrated how 3D printing can provide cost-effective and highly individualized assistive technology solutions, although extensive help is currently required. If we can empower these therapists to design and prototype solutions on their own, they can utilize in-house 3D printing to overcome several challenges in assistive technology such as limited availability, high costs, and poor fit.

*10.4.2. Budget Extra Time for Iteration and Fitting.* While it is possible to create custom accessibility solutions, the time between iterations from design to prototype can be slow. Even though it only took 2 hours to 3D print the custom stylus grip discussed earlier, the development took longer than expected. While design and print time were within reason, this project unfolded over the course of several months. The ultimate limiting factor on this project was access to the student, who was only available for testing during short therapy sessions. We were restricted both by our access to the student and by the student's availability to test out the grip. We believe this process could be faster if the end-user were able to be more involved in the design process.

### 10.5. Lessons Learned (for Researchers)

After nearly 2 years of studying 3D printing in special education settings, we have noted pitfalls and workarounds that may be insightful for future researchers in this area.

*10.5.1. Access to Participants.* Students in special education are a protected population, as they are both minors and persons with disabilities. It is important to find out during the early planning stages of a study what, if any, access the investigators will be granted with the children in special education settings. Our investigations were often limited to observation-only interactions with children.

Our strategy to gain insights about the experiences and the needs of the children as users of 3D technology and 3D-printed assistive devices relied heavily on adult faculty collaboration. We worked as partners with teachers and therapists in order to validate our observations and to gain knowledge via their hands-on interactions with students. This also afforded us more long-term wisdom to help sort out behaviors or obstacles that are specific to particular students rather than more generalizable to an ability level.

*10.5.2. How Much Support to Offer.* In order to get a realistic view of the trials associated with 3D printing in special education, we had to be careful about the type of support we provided to our participants at Site A. The other investigation sites we worked with had access to 3D printing prior to our study and did not look to us for technical support. By introducing a 3D printer to Site A, we became the primary source for technical support. Especially in the early months of the study, when the technology instructors were having repeated mechanical failures with their printer, we felt obligated to step in. We recognized that we were quickly losing participant buy-in with the technology and were able to replace their printer with a similar but more reliable model from the same printer family.

Despite the increasing popularity and the decreasing price of consumer-grade 3D printers, there are still issues of printer reliability. Among the problems that continue to plague 3D printer users are issues of file formatting and slicing errors (wherein problems with the geometry of a 3D model cannot be correctly translated to slices for the printer), prints failing to adhere to the print bed, clogs or jams in the heated extruder, and low-quality filaments entering the consumer market with manufacturing defects that can negatively impact print success or print quality. In the real world, these issues continue to impact educators of all student types. With this in mind, we tried to encourage our participants at Site A to conduct their own troubleshooting and problem documentation after we replaced their printer.

We found that while participants were quick to complain about inconsistencies with their printer, they were also very invested in solving issues on their own. It became evident the day-to-day maintenance of the printer was too much for the instructors at times, but that their determination to be self-sufficient prevented them from reaching out to us for help and slowed the progress of their class.

We suggest itemizing the support and maintenance needs of 3D printers with participants prior to study deployment. Promotional material for consumer-grade 3D printers makes the technology sound very plug-and-play and user friendly, but the reality for our participants was closer to the trial and error sometimes encountered with medium-fidelity prototypes. It is important to prepare the participants for the reliability of this technology without influencing their perception and willingness to use the printers. Talking through potential errors and hardware complications ahead of time helps manage participant expectations and creates defined roles in the troubleshooting process.

*10.5.3. Financing Technology.* On top of user training and the maintenance aspects of a 3D printer, we found that there are also several financial considerations when deploying this technology in the wild. Spare parts and miscellaneous tools need to be available to participants to care for the machine and polish off their prints. This includes extruder nozzles and print bed coatings for the machine, wire cutters for filament, and items like pliers, scrapers, and sanders for removing objects, snapping off support material, and smoothing any rough surfaces from completed designs. The filament itself needs to be kept in supply and participants will likely want multiple colors.

We found it useful to maintain an inventory of supplies provided and requested our participants at Site A to maintain a log of printer activity and repairs. Similar to diary or journal-style studies, we found that printer log information provided by participants dropped off after a short period of time and rarely contained all of the data necessary to keep accurate track of the materials being used. Still, monitoring the supplies and checking digital history of print jobs stored on the printer allowed us to keep tabs on the amount of plastic used based on total print time for the machine.

A further consideration for us was the fundraiser component of the Site A technology classroom. Because the class had an industry model wherein the students were intended to create and sell commodities based on the technical skills they were using, they were then printing and selling objects using materials provided for the study. One of our researchers made a habit of photographing and documenting items for sale to help track the designs being printed and to account for the materials used. The school was not asked to recoup costs or provide its own materials; instead, it was assumed that use and sale of printed objects were benefits of being participants in our study.

## 11. CONCLUSIONS AND FUTURE WORK

Our research has identified benefits of 3D printing in special education environments, and it has uncovered several obstacles to adoption. As 3D printing technology progresses and becomes more reliable, we believe there are opportunities for STEM engagement in children with varying abilities, providing tactile access to information and educational content, and encouraging DIY and in-house assistive device design. In extension of this work, we have also presented GripFab, a prototype modeling software to support the design of individualized AT. Findings from the preliminary testing of GripFab with therapists suggest that by offering these users appropriate tools and support, customized assistive solutions are a viable application of 3D printers.

We have also offered new insights into the perceptions of various stakeholders in special education with respect to 3D modeling and printing. To encourage the adoption of this technology in special education, we identified barriers and points of consideration for 3D printer manufacturers, 3D modeling software developers, special education institutes and accessibility organizations, and therapists. These insights have been updated from our earlier work to include explicit lessons learned on conducting field research with 3D printers in special education environments and designers with different abilities.

In the future, we will continue to work with a wider range of instructors in non-technical fields and work directly with students. We will also expand on our work with therapists and other medical professionals using 3D printing in support of accessibility and dynamic AT design. This will include further development of GripFab and similar tools coupled with longitudinal field deployments to evaluate the usability of the software and the practicality of the objects made by 3D printers.

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## REFERENCES

Paulo Blikstein and Dennis Krannich. 2013. The makers' movement and FabLabs in education: Experiences, technologies, and research. In *Proceedings of the 12th International Conference on Interaction Design and Children (IDC'13)*. 613–616.

Craig Brown and Amy Hurst. 2012. VizTouch: Automatically generated tactile visualizations of coordinate spaces. In *Proceedings of the 6th International Conference on Tangible, Embedded and Embodied Interaction (TEI'12)*. ACM, New York, 131–138. DOI:http://dx.doi.org/10.1145/2148131.2148160

Erin Buehler, Shaun K. Kane, and Amy Hurst. 2014. ABC and 3D: Opportunities and obstacles to 3D printing in special education environments. In *Proceedings of the 16th International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS'14)*.

Jodie Copley and Jenny Ziviani. 2004. Barriers to the use of assistive technology for children with multiple disabilities. *Occupational Therapy International* 11, 4 (January 2004), 229–243.

Melissa Dawe. 2006. Desperately seeking simplicity: How young adults with cognitive disabilities and their families adopt assistive technologies. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'06)*. 1143–1152.

Sean Follmer, David Carr, Emily Lovell, and Hiroshi Ishii. 2010. CopyCAD: Remixing physical objects with copy and paste from the real world. In *23rd ACM Symposium on User Interface Software and Technology (UIST'10)*. 381–382.

Gillian R. Hayes, Sen Hirano, Gabriela Marcu, Mohamad Monibi, David H. Nguyen, and Michael Yeganyan. 2010. Interactive visual supports for children with autism. *Personal Ubiquitous Computing* 14, 7 (April 2010), 663–680. DOI:http://dx.doi.org/10.1007/s00779-010-0294-8

Yingdan Huang and Michael Eisenberg. 2012. Easigami: Virtual creation by physical folding. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction (TEI'12)*, Stephen N. Spencer (Ed.). ACM, New York, NY, USA, 41–48. DOI:http://dx.doi.org/10.1145/2148131.2148143

Amy Hurst and Shaun Kane. 2013. Making "making" accessible. In *Proceedings of the 12th International Conference on Interaction Design and Children (IDC'13)*. ACM, New York, 635–638. DOI:http://dx.doi.org/10.1145/2485760.2485883

Amy Hurst and Jasmine Tobias. 2011. Empowering individuals with do-it-yourself assistive technology. In *Proceedings of the 13th International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS'11)*. ACM, New York, 11–18. DOI:http://dx.doi.org/10.1145/2049536.2049541

Shahram Izadi, Richard A. Newcombe, David Kim, Otmar Hilliges, David Molyneaux, Steve Hodges, Pushmeet Kohli, Jamie Shotton, Andrew J. Davison, and Andrew Fitzgibbon. 2011. KinectFusion: Real-time dynamic 3D surface reconstruction and interaction. In *ACM SIGGRAPH 2011 Talks (SIGGRAPH'11)*. ACM, New York, NY, USA, Article 23, 1 pages. DOI:http://dx.doi.org/10.1145/2037826.2037857

Shaun K. Kane and Jeffrey P. Bigham. 2014. Tracking @stemxcomet: Teaching programming to blind students via 3D printing, crisis management, and twitter. In *Proceedings of the 45th ACM Technical Symposium on Computer Science Education (SIGCSE'14)*. ACM, New York, NY, USA, 247–252. DOI:http://dx.doi.org/10.1145/2538862.2538975

Adam Kemp. 2013. *The Makerspace Workbench: Tools, Technologies, and Techniques for Making*. Sebastopol, CA: Maker Media.

Dennis Krannich, Bernard Robben, and Sabrina Wilske. 2012. Digital fabrication for educational contexts. In *Proceedings of the 11th International Conference on Interaction Design and Children (IDC'12)*. New York, NY: ACM Press, 375–376. DOI:http://dx.doi.org/10.1145/2307096.2307174

Ben Leduc-Mills, Jaymes Dec, and John Schimmel. 2013. Evaluating accessibility in fabrication tools for children. In *Proceedings of the 12th International Conference on Interaction Design and Children – (IDC'13)*. New York, NY: ACM Press, 617–620. DOI:http://dx.doi.org/10.1145/2485760.2485882

Ben Leduc-mills and Michael Eisenberg. 2011. The UCube: A child-friendly device for introductory three-dimensional design. In *Proceedings of the 10th International Conference on Interaction Design and Children (IDC'11)*. 72–80.

Sylvia Libow Martinez and Gary Stager. 2013. *Invent to Learn: Making, Tinkering, and Engineering in the Classroom*. Constructing Modern Knowledge Press, Torrence, CA.

Robert Lutz. 2013. Enhancing information technology education (ITE) with the use of 3D printer technology. In *Proceedings of the 14th Annual ACM SIGITE Conference on Information Technology Education (SIGITE'13)*. ACM, New York, NY, USA, 157–158. DOI:http://dx.doi.org/10.1145/2512276.2512327

Andrew Manches and Claire O'Malley. 2011. Tangibles for learning: A representational analysis of physical manipulation. *Persaonl Ubiquitous Computing* 16, 4 (July 2011), 405–419. DOI:http://dx.doi.org/10.1007/s00779-011-0406-0

Minifacture. 2013. Adjustable Bottle Cap Opener / Cap Wrench. (2013). Retrieved January 20, 2015, from http://www.thingiverse.com/thing:40131.

National Science Foundation. 2013. *Women, Minorities, and Persons with Disabilities in Science and Engineering: Special Report NSF 13-304*.

Irene Posch and Geraldine Fitzpatrick. 2011. First steps in the FabLab: Experiences engaging children. In *Proceedings of the 24th Australian Computer-Human Interaction Conference (OzCHI'12)*. 497–500.

David Rose, Anne Meyer, and Nicole Strangman. 2002. *Teaching Every Student in the Digital Age: Universal Design for Learning*. Association for Supervision & Curriculum Development.

Tides Center. 2014. Maker Education Initiative. Retrieved from www.makered.org.

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