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Making the maker movement more inclusive: Lessons learned from a course on accessibility in making

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ABSTRACT

Making and the "maker movement" have been growing in popularity as a progressive educational approach. However, researchers have leveled critiques of making as being exclusionary toward people with disabilities. In this paper, we present results from the iterative design, implementation and evaluation of *Inclusive Making*, an undergraduate and graduate level course on accessibility in making. Students in the course went through a ten-week process, culminating in the design of accessibility solutions to include communities with disabilities in making. Using qualitative methods, we chronicle students' design products, processes and learning in relation to the course iterations. Results show that when students worked with external stakeholders, their designs and learning improved. Moreover, designing for neurodiverse children required students to grapple with existing literature about making in education. We discuss insights from our work regarding the need for more accessibility research in making, and the potential of university students to promote accessible making by engaging with external stakeholders.

1. Introduction

Making activities, practices of DIY (Do-It-Yourself) with electronics, craft materials, and digital fabrication tools have grown in popularity over the last decade into a "maker movement" (Halverson & Sheridan, 2014). These activities and the environments where they often take place (e.g. makerspaces) offer many educational promises for students in schools (Lynn, Angello, Saenz, & Quek, 2017) and informal learning environments (Gutwill, Hido, & Sindorf, 2015; Halverson & Sheridan, 2014). Advocates of making argue that it provides an opportunity for anyone to innovate (Dougherty, 2013; Hatch, 2014), that children can develop positive problem solving mindsets (Martin, 2015), and that abstract STEM concepts and skills can be taught through the hands-on learning of making (Blikstein, 2013). Moreover, access to manufacturing technologies supports personal-scale fabrication, a potentially empowering affordance for people with disabilities to design their own assistive technologies (Hurst & Tobias, 2011; Meissner et al., 2017).

Nevertheless, these optimistic views are qualified with growing critiques of the ways in which the maker movement is not inclusive to non-dominant communities such as women, people of color, and people with disabilities (Seo, 2019; Siu, Miele, & Follmer, 2018; Vossoughi, Hooper, & Escudé, 2016). Therefore, a central goal of maker education research is to help solve these inequities and make it accessible to children of all backgrounds. Researchers have begun to address this inequity in several ways; through the design of maker activities for people with disabilities, the design of more accessible tools, and by suggesting guidelines for spaces to allow more equitable making (Alper, 2013; Alper, Hourcade & Gilutz, 2012; Seo, 2019). Building on this prior work, we argue that educating designers (and future designers) of technology is an important complimentary route to support the broadening of access to making by communities with disabilities. Specifically, we posit that universities should use their financial, logistical, and human resources to advance accessibility through collegiate courses. Universities equipped with makerspaces or fabrication labs (Van Holm, 2012) where students learn technological skills can orient some of their work toward the inclusion of communities in maker practices. Moreover, students graduating from technological degrees (e.g. computer science) should develop the disposition and skills needed to design technology and making tools that address accessibility (Shinohara, Bennett, & Wobbrock, 2016).

In this paper, we report on a design-based research (Reeves, Herrington, & Oliver, 2005) project on a curriculum that engages undergraduate and graduate students in designing accessibility solutions for making with local communities. We begin by describing the curriculum, its guiding theory, and in-class and out-of-class activities. We include a description of design

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changes made between the three course implementations. Then, we use bidirectional artifact analysis to chronicle students design and learning processes. Specifically, we explore design considerations that emerged as students worked with stakeholders that serve children and adults with disabilities. This paper makes the following contributions:

- We share a curriculum for teaching university students about accessible making.
- We demonstrate how university students learn to design accessible solutions for making.
- We provide design guidelines for teaching university students accessibility in making based on our iterative design.

The paper is organized as follows. The second section presents related work on making, critiques about its inequities, studies on making for people with disabilities, and university level courses on accessibility design. The third section outlines the course design, its underlying model, and concrete activities. The fourth section describes our methods, participants in the three implementations, the data we draw on, and our data analysis. The fifth section presents results with a focus on a subset of student projects, which demonstrate student learning and design processes through the course iterations. We close with a discussion of how findings from our course implementations may inform the research and practice of communities who seek to promote and create a more inclusive making.

2. Related work

2.1. The promises of making for education

Educators and researchers are increasingly looking at making as an approach to engage children with creative expression and STEM learning (FabLearn Labs, 2016; Papavlasopoulou, Giannakos, & Jaccheri, 2017; Vossoughi & Bevan, 2014). Here we describe what making is, and what its benefits are for education and society. Martin defines making as "a class of activities focused on designing, building, modifying, and/or repurposing material objects, for playful or useful ends, oriented toward making a product of some sort that can be used, interacted with, or demonstrated" (Martin, 2015). This hands-on and generative process echoes *Constructionism*, emphasizing the role of constructing shareable objects to think with and the power of big ideas (Harel & Papert, 1991; Papert, 1980, 2000). Making activities can promote meaningful student learning in areas such as digital literacy (Bekker, Bakker, Douma, Van Der Poel, & Scheltenaar, 2015), programming (Papavlasopoulou et al., 2017), and science (Bevan & Bevan, 2017; FabLearn Labs, 2016). Moreover, it may promote a "maker mindset", a positive disposition toward problem solving (Lynn, Quek, Bhangaonkar, & Boettcher, 2015; Martin, 2015).

Alongside the educational perspective, advocates of making argue that its technologies, practices, and communities promote the democratization of technology. That is, putting means of production and innovation in the hands of the many rather than a select few experts or financially privileged groups (Halverson & Sheridan, 2014). This creativity and innovativeness is celebrated in venues and publications such as "Make" magazine and Maker Faires, two leading sites of the maker movement (Martin, 2015). As we tease out in the next section, certain inequities in the maker movement limit the reach of both the educational promises and the democratizing power of making.

2.2. Critiques of inequity in the maker movement

While the argument is that the democratization offered by the maker movement can allow "anyone" to make (Hatch, 2014), voices among scholars of making have called attention to inequities in regards to who actually is included and recognized in making. Leah Buechley studied the covers of "Make" magazine and found that 85% of the people featured were men or boys, and none were people of color (Buechley, 2016). Vossoughi, Hooper, and Escudé (Vossoughi et al., 2016) elaborate on the material effects of the discourse on what counts as making and who counts as a maker. They argue that narrow definitions of making and makers represent mostly affluent white males. This representation privileges them in terms of public policy and funding as making generates excitement from public and private stakeholders. Alongside racial and gender lines, making is critiqued as exclusionary toward people with disabilities (Alper, 2013; Hurst & Kane, 2013; Seo, 2019).

The exclusion of people with disabilities from making is a significant oversight. As documented by researchers in HCI, the tools and practices of making could empower people to create or modify their assistive technologies (Hurst & Tobias, 2011). Such personal modifications may engender higher adoption rates of assistive devices that are otherwise expensive and often abandoned by users. Maker resources could also provide educational benefits to children with disabilities; for example, one can use 3D printing to visualize information and to create in-house assistive designs for students (Buehler, Comrie, Hofmann, McDonald, & Hurst, 2016). Thus, students with visual impairments can learn from 3D printed tactile maps, which would otherwise be expensive to order (Giraud, Brock, Macé, & Jouffrais, 2017). Neurodiverse children too can benefit from maker activities and produce meaningful and personal artifacts (Spiel, Makhaeva, & Frauenberger, 2016). Taken together, it is evident that the tools and practices of making, when made accessible, can have positive implications for people with disabilities.

2.3. Accessibility in making

For making to be inclusive, the spaces (Alper, 2013; Bennett, Stangl, Siu, & Miele, 2019; Peppler, Halverson, & Kafai, 2016) and tools (Seo, 2019) through which making takes place must be made more accessible. A growing body of work in disciplines such as HCI and learning sciences explores ways to create accessible maker tools, activities, and environments for a variety of communities. Researchers have developed E-Textile workshops for people with visual impairments (Giles, Keynes, Keynes, Petre, & Keynes, 2018) and people with intellectual disabilities (Gotfrid & Shinohara, 2018). Others have designed maker tools and toolkits that address hearing or vision impairments (Hurst, 2011; Hurst & Kane, 2013). Alper, Hourcade and Gilutz (2012) extended popular guidelines for designing construction kits for children (Shinohara, Bennett, Wobbrock, & Pratt, 2017) to address the needs of makers with diverse abilities. Alper (2013) also calls for mixed ability makerspaces where youth with and without disabilities can engage in making in an equitable way.

Taken together, we see that through design work, spaces, and tools (both software and hardware) can be more accessible to people with diverse abilities. Nevertheless, to do so on a larger scale requires two efforts. First, technology manufacturers need to make accessibility a central consideration in their design process. Secondly, advocates of making should introduce maker activities into their local communities and support people with disabilities while drawing on human and financial resources. We argue that universities that have the resources — students, makerspaces, and funds, can and should take part in these efforts. They can train accessibility-oriented students while engaging them in community outreach around accessible making.

2.4. Collegiate design courses for accessible computing

In this paper, we share the design and findings from a university level course called Inclusive Making. We argue that such courses can make university students into agents of change in their nearby communities (Putnam, Dahman, Rose, Cheng, & Bradford, 2016; Shinohara et al., 2016). Furthermore, we argue that these experiences can help the field reimagine inclusive making activities and makerspaces. Our work echoes a current impetus to place accessibility as a central theme in CS education. Studies show that design courses that focus on accessibility lead students to develop an understanding of the importance of accessibility (Shinohara et al., 2017). Students also realize that accessibility should be every designer's responsibility and not solely the responsibility of people with disabilities or dedicated specialists (Ludi & Ludi, 2007; Shinohara et al., 2016). An important aspect of successful courses on accessibility is engaging students with external stakeholders with disabilities. Taking this approach can mitigate students' biases and misconceptions about disabilities (Ludi & Ludi, 2007; Shinohara et al., 2016). The course that we describe in this paper has many of these goals, but in the context of critically examining making.

Looking at this related work together, we see the following logical argument. Making offers a range of promises in terms of educational and material benefits. While making is gaining in popularity around the world, continuous attention should be paid to issues of equity. Within this effort, we focus on work to include communities and children with disabilities in making. We propose a solution in the form of a university level course. We ground this solution in ongoing work aimed at educating future designers of technology to design accessible technologies who will create an impact on society.

We position this curriculum as a contribution to the field of making in education. In particular, the course is a model for teaching accessibility in making to university students and permeated into the broader community. In prior work (Worsley, Bar-el, & Worsley, 2020) we reported on student's motivation and dispositions in the context of the course. In line with this special issue, we center the remainder of this paper on how students designed for accessibility while taking part in the course, and what lessons we can learn from their designs regarding accessibility of making for children with disabilities. Specifically, we ask the following research questions:

RQ1: *How do students' designs and understanding of accessibility solutions for making evolve through a university level course?*

RQ2: *How does working with external stakeholders affect students' designs and understanding of accessible making solutions?*

3. The current course — Inclusive making

In this paper, we report on our iterative design and implementation of Inclusive Making, a collegiate course on accessibility in making. We take a design-based research approach (Barab, Squire, Barab, & Squire, 2009; Reeves et al., 2005), which includes stating our design decisions, describing our iterations, and evaluating our findings. In the following sections, we describe the curriculum design. We begin by presenting the three bodies of literature that served as the theoretical foundation of the curriculum. We then move to a concrete description of the course activities and articulate changes made between the first and second iterations.

3.1. Theoretical underpinnings

In addition to the aforementioned background literature, we grounded the design of the course in principles taken from three primary bodies of literature: making, User-Centered Design (UCD), and Critical Disabilities Studies. We covered making in the above related work section. UCD is a family of design approaches that centers on user feedback (Gould & Lewis, 1985). Following UCD designers use a variety of techniques to learn from users throughout their design process; in identifying the problems, coming up with solutions, and testing prototypes (Rubin & Chisnell, 2008). In Inclusive Making we emphasized ability-based design (ABD) (Wobbrock, Kane, Gajos, Harada, & Froehlich, 2011), an extension of UCD which asks designers to focus on the user's abilities rather than their "dis-ability". This emphasis is valuable for two reasons. First, it stresses the need to interact with people with disabilities over relying on stereotypes or assumptions about what someone can or cannot do. Second, ABD calls attention to the variation in ability between and within every potential user of technology based on different contexts (Wobbrock et al., 2011). Therefore, we used ABD to inform students' engagement with users, to mitigate stereotypical assumptions[1] and to show the generalizable value of focusing on diversity in ability.

We also drew on Critical Disability studies as a guiding lens. Critical Disability studies represent scholarship and political action that challenge the perspective and policies stemming from the medical model of disability. The medical model defines people with disabilities as having an internal problem and the treatment as a way to allow said people to be "normal". Counter to this view, the social model of disability focuses on the personhood of the individual rather than their impairments (Worsley et al., 2020). The social model does not deny the existence of physical impairments; rather it focuses on the experience of disability being the result of an interaction between the physical reality and other socially determined factors such as material designs and social or political powers (Oliver, 2013).

To summarize the theoretical underpinnings of Inclusive Making, we designed the course with a lens of Critical Disability studies in order to help students unpack the various socially constructed hurdles that may exclude people from participating in making. Such unpacking includes an understanding that makerspaces and tools are not neutral, rather they are built on assumptions that may not fit the abilities or motivations of all users (Chu, Saenz, & Quek, 2016; Martin et al., 2018; Seo, 2019). Additionally, students learned and used UCD to design accessible making experiences for people with disabilities that problematized many implicit assumptions about making and makers.

3.2. Iterative course design

In line with a Design-Based Research (DBR) agenda (Barab et al., 2009), we chose to draw on conjecture (Sandoval, 2014) maps as a tool to capture our iterative design process, the connection between the course's theoretical underpinning, design elements, and our intended outcomes. Conjecture maps serve as a representational device for documenting and communicating design research on the development of educational interventions. We share two conjecture maps to explain changes made between the course iterations and frame our results in terms of the intervention outcomes.

[1] We guided students to focus on people's abilities rather than their disabilities, as a way to avoid relying on assumptions or stereotypes. However, we recognize that some people feel that their disabilities are central to their identities. Several disabled authors regard this erasure as "Epistemic Violence" (Good & Bennett, 2020).

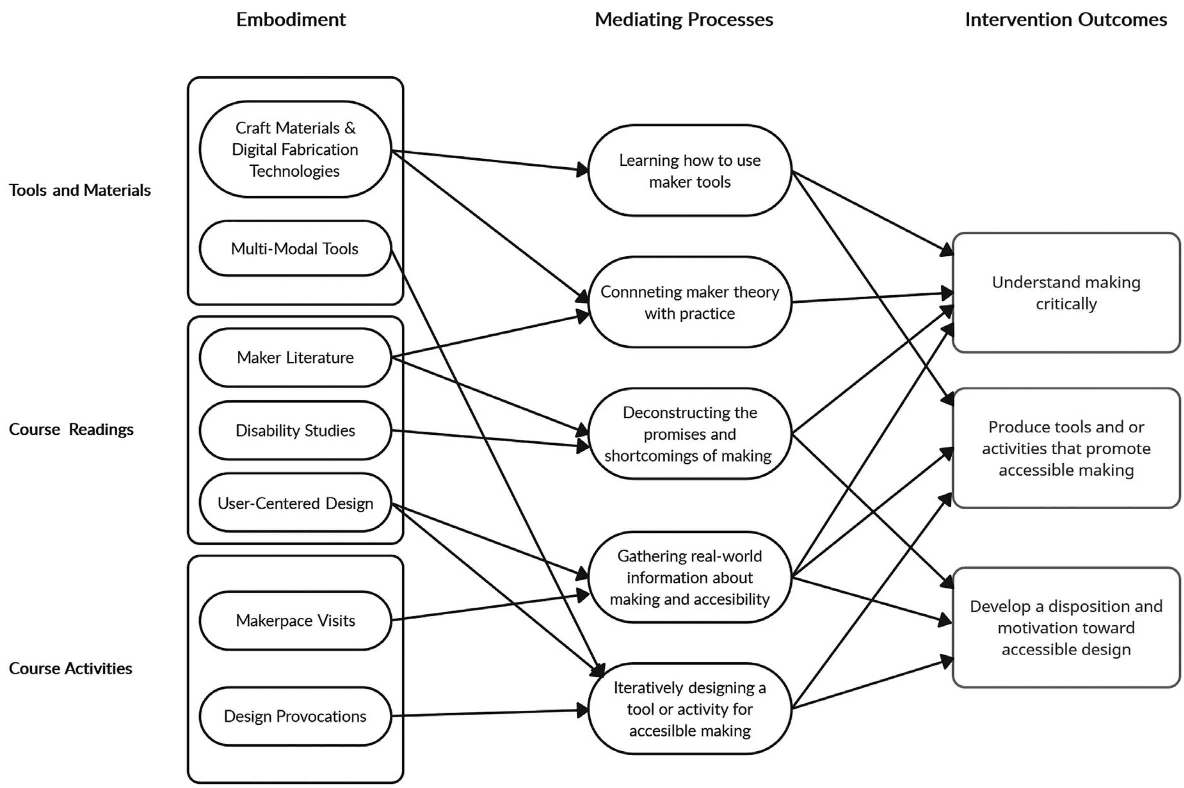

Fig. 1. A conjecture map for the first iteration of Inclusive Making.

Inclusive Making is a combined undergraduate and graduate class that is cross-listed in the Schools of Engineering and Education. The class met once a week for three hours and included a mixture of lectures, in-class, hands-on design challenges, and group discussions. Besides these in-class activities, students took part in out-of-class activities and went through design processes. In the following section, we elaborate on what these activities looked like, what their goals were, and what changes we made between iterations.

3.2.1. First iteration

Fig. 1 illustrates the conjecture map we created as part of the design of the first iteration of Inclusive Making. Our high-level goals for the course were for undergraduate and graduate students to engage in hands-on learning of maker tools, read and apply ideas from the aforementioned three bodies of literature, and undergo a UCD process toward creating accessibility solutions for making. As presented in the intervention outcomes, we hypothesized that through this ten-week course; students would critically analyze making, design accessibility solutions, and become more inclined to incorporate accessibility as part of their future work.

Within this conjecture map, there are three key features: (A) the tools, readings, and activities that form the embodiment of the curriculum; (B) the processes that mediate and evidence how students engage with the tools, readings, and activities to construct new skills and understanding; and (C) the intended outcomes of the embodiment and mediating processes. In the following paragraphs, we describe the class activities, out of class activities, and group projects we designed for students to complete as part of the course.

In-class activities

We designed in-class activities to give students the opportunity to collaborate with their peers, participate in hands-on projects, apply design techniques, and discuss the guiding literature. The majority of the hands-on, in-class activities use household arts and crafts supplies such as Popsicle sticks, felt, paper plates, pipe cleaners, and hot glue. Others introduce students to the basics of using digital fabrication tools such as laser cutters and 3D printers. Additionally, students experiment with multimodal tools such as tactile, speech and gesture based interfaces. Two of the in-class activities aim to help students think about the assumptions and biases of maker tools in relation to users with different abilities, specifically makers with visual impairments. For example, we adopted an activity developed by a blind doctoral student who explores the design of accessible programmable maker kits. In this activity, some students wore a blindfold while trying to learn how to program a robotic toy. Blindfolded students tried to follow a set of instructions and program a sequence of actions for the robot to complete, such as lighting different LED lights. In the meantime, the non-blindfolded students were guided to use some accessibility best practices like verbally describing objects and guiding someone's hand through a new tactile experience. These two activities gave students a chance to question the assumptions that designers build into many maker kits such as catering to vision rather than multiple modalities. While conducting this empathy technique, we were cautious to not suggest that wearing a blindfold accurately represents living with a visual impairment (Silverman, 2015). Instead, we framed these activities as a primer for students to pay attention to the ways in which the designs of maker tools matters in relation to sensory abilities.

Out-of-class activities

In line with a UCD approach, students also sought out communities and potential users in relation to making. These out-of-class activities afforded students opportunities to develop an understanding of how makerspaces addressed or failed to address access and to develop empathy with people with disabilities in relation to making. In the first iteration, these activities were visiting two or more makerspaces and having a discussion with a person who identified as having a disability. The makerspace visits served as opportunities for students to see what makerspaces look like outside of course readings and of a fabrication space on campus. Moreover, by comparing different makerspaces and talking to staff, students could see first-hand the needs for accessibility, and if and how spaces were addressing these needs. The dialog with a community member served as a chance to mitigate students' biases regarding disability by learning from a lived experience.

Group projects

Over the course of Inclusive Making, students are required to work in groups of two to four and submit three design assignments. In the first iteration of this course, these assignments were distinct design prompts; all aimed at designing accessibility solutions for people who are either blind or have low vision. The first, "*Navigating a makerspace through the senses*" was an encouragement to think about how a person with visual impairments might arrive and be introduced to making. The second, "*Beyond Vision*" encouraged students to come up with an interface or a set of activities that would allow someone with visual impairments to create or learn something new inside a makerspace. The third, "*Upgrade*" asked students to take the first, second, or a combination of the two projects, and develop a final design.

3.2.2. Second iteration

After the design and implementation of the first iteration, we reflected on student projects, impromptu changes we had made that deviated from the initial conjecture map, and our observational notes from lectures and group discussions. Following the iterative approach of DBR, we made three key changes to the course. Fig. 2 illustrates this second design of Inclusive Making. The first change was the addition of a recurring in-class activity of concept mapping the course readings. From observations of first year reading discussions and students' assignments, we found that students struggled to make connections between the three bodies of the underlying literature. We understood this as a need for deliberate scaffolding (Chang, Sung, & Chen, 2001) given that for many students, the course was the first time learning about making, UCD, and Critical Disability studies. Therefore, in the second iteration, we dedicated 15–30 min per week to building concept maps through classroom discussions using a shared google slides presentation. This recurring activity helped scaffold the discussion and synthesis of the three bodies of literature. We intended for students to use this synthesis and representation to deconstruct making in terms of its promises for education and society and the critiques of inequities in making. We hoped that such a synthesis would help students identify how their work could tackle issues of access in making.

The second change was an additional out-of-class activity of volunteering at an organization that provides accessibility-related services. This volunteer activity, placed at the start of the course, was an attempt to push students to develop relationships with local organizations. We added this activity for two reasons. First, we found that students in the first iteration took a long time to find and contact organizations or users if they wanted to. Second, prior university courses on accessibility design show that through work with external stakeholders, students' awareness of accessibility increases, and their designs improve (Ludi & Ludi, 2007; Shinohara et al., 2017). We drew on our existing work with local organizations and on researchers in our university's networks to generate a list of potential partnering organizations. Students received this list before the first class session, but were also encouraged to reach out and work with other organizations as they saw fit. Students wrote a short reflection paper after their visit, which in many cases, helped motivate ideas for their final projects.

The third change was the addition of a second design track that students could choose to take instead of the original three prompts. This track allowed flexibility for groups who chose to work with an organization that did not serve patrons who are blind or with low vision. Moreover, in this track, the three design assignments took students through rounds of prototyping, testing, and iterating toward a specific design solution.

4. Methods

We asked what students would design for accessibility in making. Moreover, we asked how these designs differed through course iterations. To answer this research question, we analyzed students' artifacts as well as their design processes. We start by providing an overview of the students who took the course and then describe the data we collected and our analytic approach.

4.1. Participants

The implementations of Inclusive Making saw a combined enrollment of 84 students. Computer science undergraduates made up more than 50 percent of enrolled students within each of the three course offerings. In addition to computer science undergraduates, nearly one third of the participants were doctoral students. Some of the doctoral students were from interdisciplinary fields that included computer science and another discipline, while several were from the School of Education.

4.2. Data collection and analytical approach

To answer the research questions, we focused on students' design process in relation to the three course iterations. We used bidirectional artifact analysis framework (Magnifico & Champaign, 2007), an analytical approach for examining learning through design processes with digital means. In this analysis, the researcher traces backwards from an artifact to the origin of its design, as well as following the initial idea all the way to its final form. By viewing the design process in these two directions, one can understand how learners arrived at a given product, as well as how the intervention (i.e. the particular course iteration) affected the design process (Halverson & Magnifico, 2013).

We followed the three steps of bidirectional artifact analysis, *Identify, Document, and Construct* (Halverson & Magnifico, 2013) We started by identifying student teams' final artifacts. These included images of the design itself, as well as final written assignments where students situated their design process within literature from the course readings. We then documented available data relating to the artifacts' design process. These data included students written design assignments, reflections on work with stakeholders, and communications with the course instructors. Finally, we constructed narratives that capture the development of the designed solutions for accessibility in making; first going backwards looking at how later designs referenced and built on earlier steps, and then looking at how the earlier steps affected subsequent design decisions.

5. Results

To answer our research questions, we examined students' designed solutions for accessible making in relation to the course's iterative design. Throughout the course implementations, student teams designed twenty-seven projects. In the first implementation, students generated nine final projects, none of which involved collaborating with external organizations. In the second and third implementations, students completed eighteen

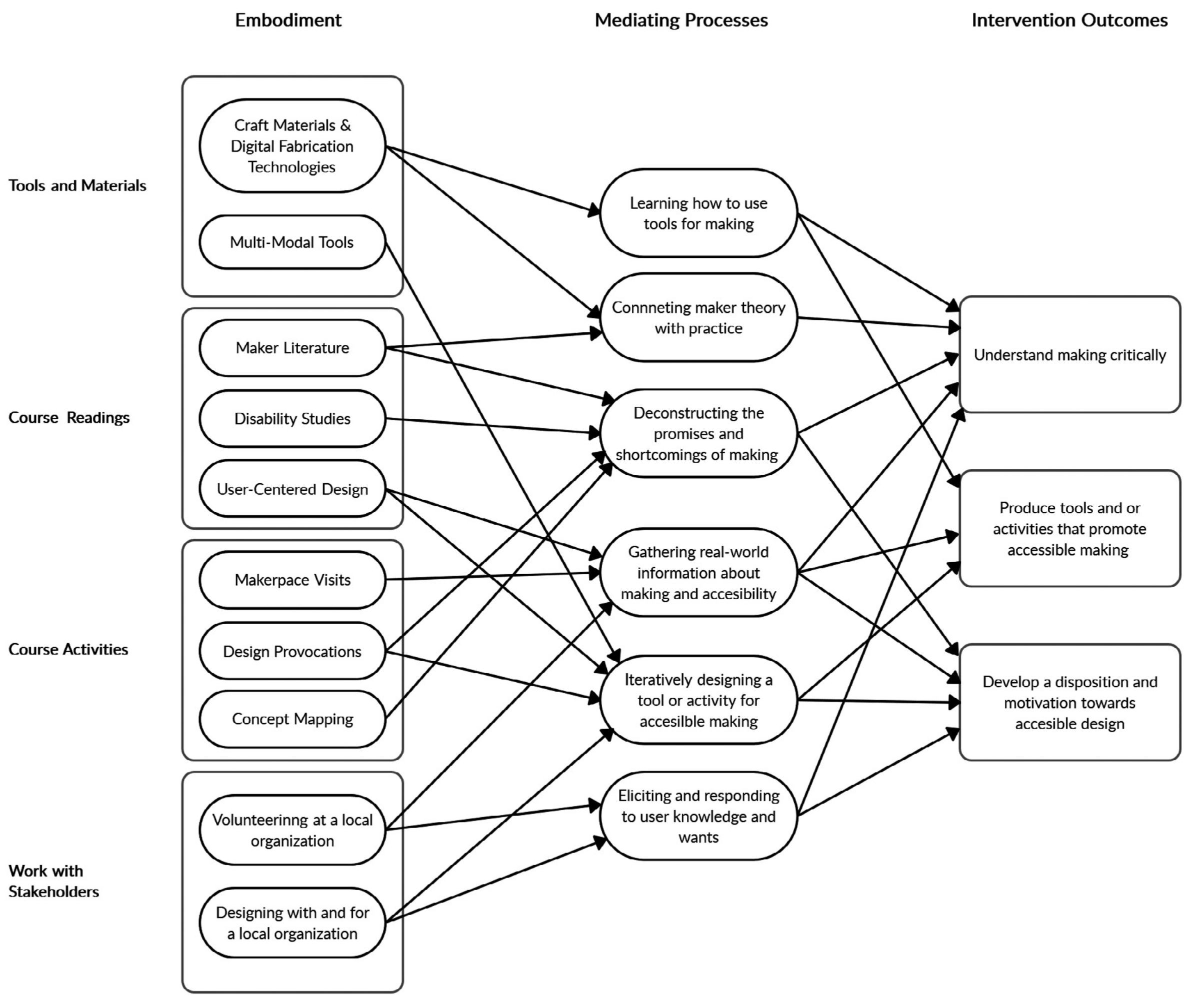

Fig. 2. A revised conjecture map for the second iteration of Inclusive Making.

projects, seventeen of which were in collaboration with external organizations. These numbers reflect the finding that most students who engaged with external stakeholders early in the course, decided to pursue a quarter long design cycle with these communities. As we will describe in the following paragraphs, this work with external stakeholders changed students' design processes qualitatively, and the ways they construed and positioned making.

To demonstrate these differences in student design and learning based on the course iteration, we present a bidirectional artifact analysis of four projects. Tracing backward chronologically, we show how final products relate to early stages in the course. These reflect differences in the courses design. Moving forward in time along the design cycle, we show how students learned about making, and design for accessibility in terms of their products and written texts. We begin with two projects from year one, and then move to two projects from years two and three respectively.

Projects from the first iteration

As stated above, in year one, students completed three design assignments toward accessible making. They were not required to volunteer and collaborate with external stakeholders. During the first iteration, students designed projects that were predominantly technological proofs of concept. These focused on providing multimodal tools or workflows, aimed at affording people with sensory disabilities either to navigate a makerspace or to operate a particular device found in maker contexts.

Project 1: 3D scanning for people with visual impairments

For their final product, (Fig. 3 left) students created an affordable setup and workflow for scanning objects for 3D printing. The setup includes an XBOX Kinect V1 and SKANECT software (Fig. 3 right). The intended use case is for the setup to be placed in a makerspace for people with visual impairments. Users mold an object using a variety of materials such as playdough and clay. They then place the mold on a spinning apparatus such as a chair and slowly rotate the object in front of the Kinect. The students suggest using an on-screen narrator when the user uses the computer.

Moving forwards through their iterations, we see that throughout the three design provocations, the team was experimenting and working on the scanning workflow. They began by borrowing a professional 3D scanner from the instructor's lab and experimenting with it. However, noting that this solution might not be available to all, they opted to try a more affordable solution, the XBOX Kinect V1. Their process then focused on testing this system by creating objects with a variety of household craft materials. For their final version, they focused on ways to optimize the scanning procedure by creating different rigs for an even rotation of the object in front of the Kinect, the best of which was a chair with a string attached for a putting toward a constant speed.

Looking at this project, we see two points that echoed throughout the work of teams during year one of the course. First,

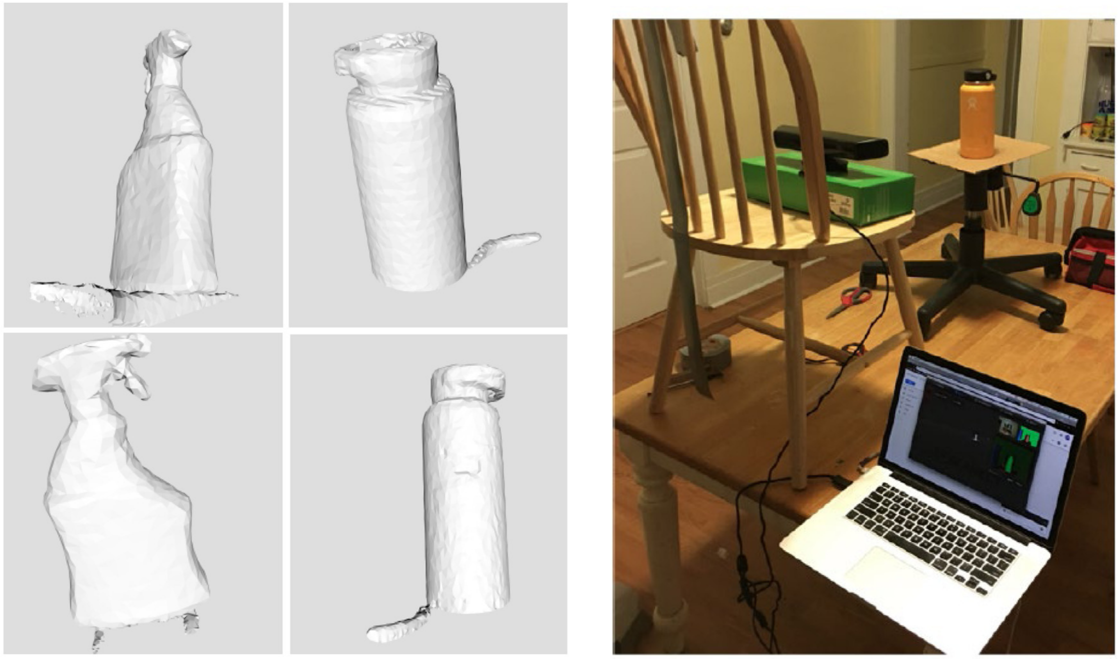

Fig. 3. Scanned objects that students tested with the 3D scanner (left). Students testing a workflow prototype using the XBOX Kinect and a rotating chair (right).

the students focused on traditional making technologies, such as 3D printing. They then proceeded to design an accessibility solution for 3D computer-aided design based on assumptions about the difficulties of people with visual impairments. Second, we see a focus on creating a technological proof of concept. This is evident in the below description of their final product.

"Through two earlier projects, the process of utilizing a 3D scanner and printer to recreate an object was researched as a possibility for opening up Makerspaces to those with visual impairments. In this final project, the process is refined, and eventually curated into an at least feasible methodology".

Juxtaposing the conjecture map with this group's product, we see that the first and last mediating processes were central to their design. The team learned how to use 3D scanning technology while iteratively designing an accessibility solution. In terms of critically examining making, the students argue that CAD technologies rely on the visual modality and attempt to address this shortcoming. However, they do not seem to grapple with the accessibility of making beyond that. These themes can be seen in another project from year one.

Project 2: Accessible Carvey

Similar to the above project, this team wanted to make digital fabrication more accessible to people with visual impairments. Their project sought to address both the design of a printable model and the use of a device to fabricate an object. The technology they focused on is the Carvey, a desktop, computerized numerical cutter (CNC) that makes 3D cuts in a variety of materials. Their final product (Fig. 4) includes two parts. The first part was using a sensational blackboard and an Equil Smartpen2 to allow users to sketch a design and get feedback about what would be transferred to the program. The sensational blackboard creates a raised image of a sketch in response to pressure from a pen. The second part of the design is a tangible interface to replace the graphical user interface of the Inventables website. A mockup of the website was made in Scratch (Resnick et al., 2009). A set of tangible areas that utilize the Makey Makey kit (Silver, Rosenbaum, & Shaw, 0000) connected to aluminum foil buttons trigger audible feedback. One area for example, allows the user to feel what a piece carved at four different depths feels like. After choosing a target depth, the user clicks on the corresponding button.

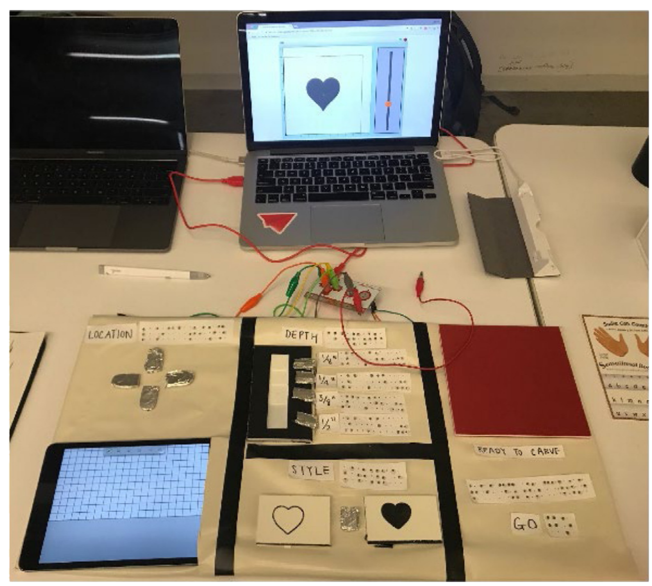

Fig. 4. The tangible interface for the Carvey milling machine.

Moving through the project timeline, we notice that the team started by interviewing a person with low vision. Through this interview, they learned that good design to him meant being able to independently use a piece of technology on the spot. From this interview, they created a persona of a blind individual who wanted to participate in making. Then they went to a makerspace on campus and observed the process students underwent when using the Carvey. This included sketching on paper, creating a digital file, uploading the image to the designated website, setting up the Carvey with the right materials and executing the print. Based on the persona that they came up with, they determined what potential pain points might be in this process for an individual with low vision.

"*The major pain points of the current system are sketching/drawing on paper and converting that into a electronic file, navigating the Inventables website as seen in* Fig. 3*, setting up Carvey with the correct parts and materials, and knowing how to troubleshoot Carvey when an issue arises during the machining process.*"

When testing their prototypes, the team relied on blindfolded peers. These tests led to changes such as "*iterating on the location choice feature, and incorporating audio with every action.*" What is absent from this design process, is the feedback of actual users with visual impairments. While some of the pain points identified by the team may be valid, it is also likely that people with visual impairments could have creative solutions already to address these difficulties (Bennett & Rosner, 2019).

Taking these two projects together, we see a design process that focuses on making digital fabrication more accessible by creating tangible interfaces for systems that otherwise rely on graphical user interfaces. From the teams' written assignments, we see that their learning centered on experimenting with the technologies themselves and noticing how the technologies are not designed with the visually impaired in mind. However, in terms of designing for accessibility, the students did not ground their work in the lived experience of real users with disabilities.

Projects from the second iteration

Following the changes made to the course in the second implementation of Inclusive Making, we saw a shift in student design and learning. In terms of the creative process, students worked proactively with external stakeholders, grounding their designs in stakeholder needs and conducting multiple rounds of ideating, prototyping, and user testing. Moreover, we saw an attempt to create impactful and sustainable solutions that could remain in use after the students left the site. In terms of student learning, teams seemed to grapple more explicitly with what making is, how it was relevant to the particular problem stakeholders wanted to address, and with tensions between maker literature and designing for children with disabilities.

Project 3: Learning about Social Media

Working with a non-profit that provides life skills and employment training for neurodiverse youth, this team developed a 3-part interactive activity for learning about sharing and safety in social media. The first activity has students build a profile on a printable sheet. The goal of this was to teach students what is and is not acceptable information to place on a profile. The second activity has students sitting in a circle, passing around a ball of yarn and sharing a news updates to simulate updating one's social media feed. As part of this activity, example sentences provide scaffolding for formulating a post (Fig. 5 left), and blocks with emojis scaffold student reactions to peer posts (Fig. 5 right).

While visiting the site, the team saw that the space included a room for arts and crafts and heard from the director that a significant challenge they face is finding activities that elicit social communication and social skills. The team initially proposed three ideas to staff at the non-profit, which included creating a music box, a moveable 3D puzzle and the social media activity. The staff wanted the team to pursue this last project "*due to its ability to convey the idea of an online social network, the interactive engagement of participants in communication and emotional expression, and easy replicability as well as flexibility for a wide range of participants*".

Again, while this activity might not fall under the definition of making for some, the team made sure to argue what aspects of making influenced their activity design. First, the team wanted the activity to be hands-on and provide physical scaffolds such as the emoji blocks. Second, the team drew on maker literature in designing the activity to be failure-positive (Martin, 2015). Finally, the team recognized that the activity did not involve high or low-tech kits and tools that are often found in makerspaces; however, they state, *"While utilizing technology was in the initial design ideas, we realized an easily replicable activity had more value"*.

Project 4: Uncreative Making

Another team from the second iteration created a final product for a K-8 school that serves students with special needs, primarily cognitive impairments. The design comprised of a toy truck that runs up and down a wooden track (Fig. 6 left) and two controllers that allow a student to drive the car to one end and wait for another to reciprocate. The project aims to serve as an activity for students with cognitive impairments to learn about cause and effect within a social context. The final product developed from ideas on a delivery system (Fig. 6 right) with which the school students could practice turn taking and observe their and peer actions at play.

Tracing back we see that the team made several choices based on feedback from visits, observations at the school and conversations with school staff. This feedback informed the team about students' needs and gave them information that was relevant to the stakeholders. The goal of the activity stemmed from a request by a teacher during the initial visit "*students need to learn and understand that their actions have direct consequences*". The choice of a delivery system and eventually a truck activity stems from the observation that many of the students benefited from movement and action-oriented activities in order to maintain engagement. However, at the same time, the team disabled sounds in the truck to avoid overstimulation.

While making these design decisions, the team noted that at times that they had to grapple with their understanding of making from the literature in relation to the stakeholder's context. In their mid-project report, they summarize takeaways from two site visits stating that the designed tasks must be straightforward, repetitive, and controlled. In their final assignment they write, *"We began this project initially believing that our activity should align with traditional maker practices, emphasizing creativity and self-expression to encourage students to build toward a long-term, more "meaningful" project"*. However, the teacher reported that her students have not displayed motivation toward creative self-expression and that during previous art activities, the facilitators ended up doing all of the work. In their final assignment, the team argue why their activity aligns with making as they understand it. *"We argue that activities like the Truck Track can be considered making because the point is not to create a product, but to help reach one's full potential (while citing Halverson & Sheridan, 2014). This is accomplished by making abstract ideas concrete through tasks (citing* Blikstein, 2013, *such as the idea of one's actions having consequence"*.

We see in the team's argumentation a grappling with the meaning of making, its objectives, and how it may apply for neurodiverse children. Specifically, we see the focus on one aspect of making, rendering abstract ideas concrete through hands-on learning. It is worth noting, that while this activity might not look like a traditional maker activity, it does share some characteristics with a common exhibit found in makerspaces and tinkering studios, marble machines (Gutwill et al., 2015). Marble machines too are static wooden contraptions that allows children to create reaction chains much like a Rube Goldberg machine. Whereas this particular activity does not result in a manufactured product, it is a tinkering activity allowing children to interact collaboratively with variables.

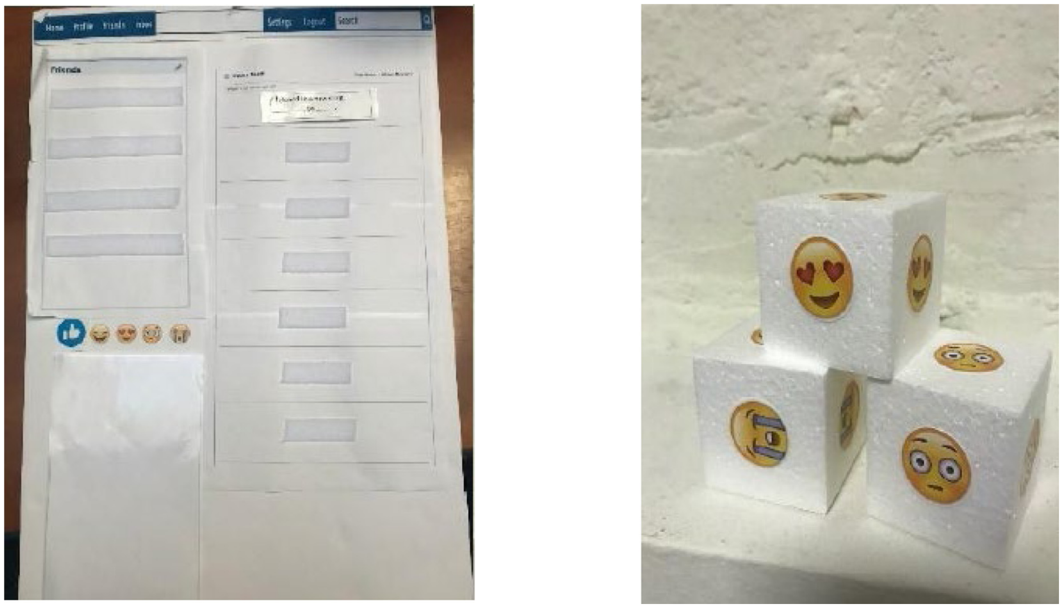

Fig. 5. A tangible social media profile made of paper and Velcro strips (left). Emoji blocks for reflecting and communicating emotions (right).

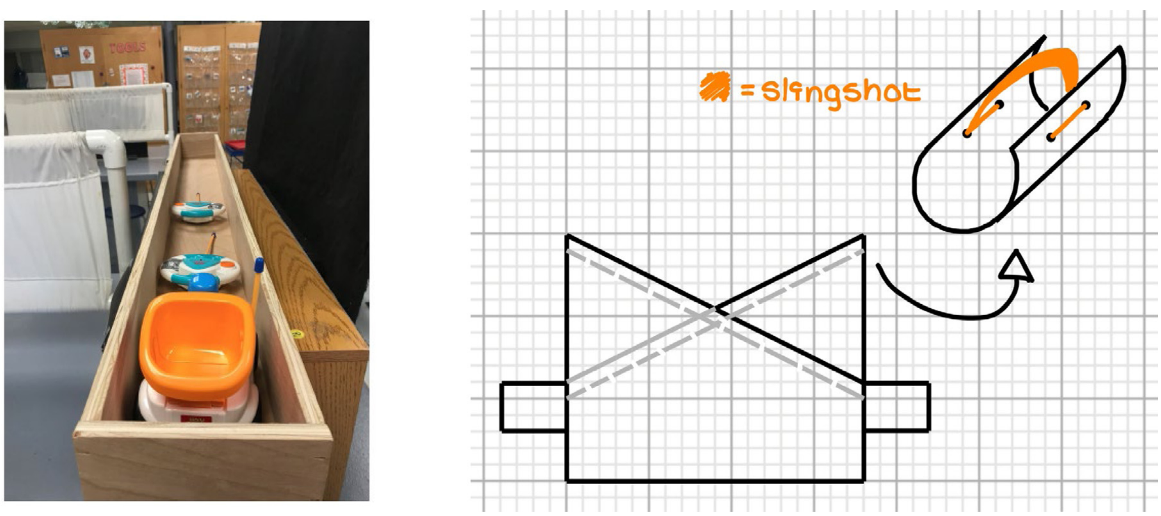

Fig. 6. The final wooden track, with the toy truck and two remote controllers (left). An initial sketch of a reciprocal delivery exhibit (right).

6. Discussion

In this paper, we presented results from the iterative design, implementation, and evaluation of an undergraduate and graduate level course on accessibility in making. In this course, teams of students spent ten-weeks designing accessibility solutions to render making more accessible for adults and children with disabilities.

We reported on the design of the Inclusive Making course. We outlined the theoretical underpinnings of the course as grounded in making, User-Centered Design, and Critical Disability studies. We then detailed the course activities and changes made between the first and second iteration of the curriculum. The relation between course activities and the intended educational outcomes were represented using conjecture maps (Sandoval, 2014). With these educational objectives in mind, we conducted a bidirectional artifact analysis (Halverson & Magnifico, 2013) to examine students' design processes and learning in relation to the course iterations.

Our first finding relates to the effect of external stakeholders as part of the course's second iteration. In the first iteration, where students were not required to volunteer with organizations, teams did not work with external stakeholders throughout their design processes. In the second iteration, students volunteered with organizations that serve patrons with disabilities. A majority of these students chose the second design track of working with external stakeholders throughout their 10-week design process.

Students' work with external stakeholders led to a number of qualitative differences when compared to student work without stakeholders. The implementation of the final products differed between the two iterations. In the first year, students created technological proofs of concept. These prototypes demonstrated that one could interact with a particular maker device through different modalities. In the two example cases, the teams designed interfaces that used tangible and auditory modalities to substitute the graphical user interface of digital fabrication technologies and make them accessible to people with visual impairments. In contrast, teams that engaged with external stakeholders, did not focus on proofs of concept, and instead created prototypes that were implemented at stakeholder community sites to various degrees. In the two examples from years two and three, the teams left their activity materials at the sites, thus allowing staff and youth to continue to conduct the intended maker activities.

An additional difference between the projects is the processes that teams underwent when working with stakeholders or not. When working with organizations, students grounded their goals, ideas, and prototypes in stakeholder experiences. This manifested in the choice of tools and activities. Students who worked without stakeholders tended to choose the makerspace as a whole or a particular maker device and to design a technological tool that could make its use more accessible. In contrast, teams that worked with organizations started by visiting their site and identifying a goal or problem that maker activities could meet. This led in some cases, to the choice of nontraditional maker activities or drawing on ideas from the maker movement in service of stakeholder goals. In terms of ideating, and prototyping, teams that did not work with stakeholders either created personas as in the first example, or worked generally under assumptions regarding potential users as in the second example. Teams that worked with stakeholders, talked to staff and or patrons at the sites as they defined the problems and came up with potential solutions. To test the prototypes, teams that did not work with stakeholders conducted user tests with students who do not have disabilities, such as blindfolded peers. In contrast, teams that engaged with stakeholders took their prototypes to test with adults and children at community sites.

This finding relates to previous work on the positive effect of engaging student designers with external stakeholders for empathy, design thinking, and design outcomes (Ludi & Ludi, 2007; Shinohara et al., 2017). In our work, we found that engaging with external stakeholders once, motivated a majority of students to choose to continue this engagement throughout their course. This engagement, improved students' design processes and allowed them to consider factors such as learning goals, motivations and pedagogy rather just the physical design of maker tools. Moreover, engaging with external stakeholders helped orient students to the lived experiences of people with disabilities and their context, including educators and caregivers. This echoes a recent critique of empathy techniques and a call for designers to shift from "being like" to" being with" (Bennett & Rosner, 2019).

Our second finding pertains to the design considerations that students faced when designing maker activities for children with intellectual disabilities. These considerations reflect tensions that students grappled with when negotiating between stakeholder needs and maker literature. In his seminal article, Blikstein (2013) warned of the keychain syndrome[2], a phenomenon that pervades many informal educational spaces. Blikstein observed that when given access to digital fabrication tools (e.g. 3D printers) students may end up mass-producing trivial products such as keychains. He argued that careful design of activities, facilitation strategies, and curricula should challenge students to steer away from repetitive trivial work and rather make their work more complex over time.

In the fourth example, the students ended up designing an activity that was simple and repetitive. The teacher wanted her students to have an activity about cause and effect that involved social interaction. The undergraduate students had to navigate designing an experience that was developmentally suitable while still drawing on making. They noted in their written assignments that while they began by wanting to introduce a traditional maker activity that would focus on self-expression, through discussions with the schoolteachers and observations, they chose to design a repetitive and very constrained activity. On the one hand, this design decision follows Blikstein's call for deliberate structuring of activities. On the other hand, it nuances the "pitfall" of triviality and repetition when designing for children for whom repetitive and simple tasks are valuable.

6.1. Implications

This work has a number of implications for research and practice. The results show that the relatively scarce attention to people with disabilities in the maker literature plays a role when designers attempt to create accessible maker activities. This is especially the case when designing for neurodiverse children. Future research should shed light on neurodiverse makers, and share their lived experiences, learning, and creations within the maker movement. Such work would serve as both a representation of a more diverse population of makers, as well as inform researchers and designers of maker tools and activities.

Student designs in this course, especially those who provided stakeholders with the activities, demonstrate the potential of university students to support the inclusion of children with disabilities in making. We believe that universities and colleges that have the appropriate logistical and human resources should engage in promoting accessible making activities. This effort would augment ongoing trends in the maker education field of introducing making to formal education (Lynn et al., 2015) and promoting gender and racial equity in making (Holbert, 2016; Pinkard, Erete, Martin, & McKinney de Royston, 2017).

The university students were motivated to engage with stakeholders throughout the quarter long course when given the opportunity to do so following the volunteer assignment. This engagement led to a number of qualitative differences in their design and understanding of making. Researchers and practitioners interested in teaching accessible making should promote student engagement with external stakeholders. The reasons for this are twofold. First, to support the learning of design students (Ludi & Ludi, 2007; Shinohara et al., 2017). Second, to create a real world impact by better designed solutions that stakeholders and other users may use.

6.2. Limitations and future work

This paper has a number of limitations. As displayed in our conjecture maps, the course has three outcome goals. In this paper, we examined the first two, for students to understand making critically and to design accessibility solutions for making. Bidirectional analysis allowed us to analyze student products and self-reported process and thinking. However, to document a reliable change over time in students' deconstructed concept of making requires a pre-post analysis. Future studies should address university students' understanding of making as it develops throughout an accessibility course rooted in critical disability studies.

The second limitation of this work is its backgrounding of stakeholders' experiences. A central motivation of this research is to produce real world impact through students' designs and work with local communities. In our work as designers, instructors, and researchers of the course, we focused on the design and learning of our students. This backgrounds what learning may or may not have occurred among the stakeholders and specifically the children who participated in the maker activities. In future work, we plan to promote a prolonged engagement between students and stakeholder communities and to study the experience of both parties.

[2] The term 'keychain syndrome' includes a metaphorical medicalization that may serve to reify negative perceptions of disability. Our acknowledgment of the underlying pedagogical concern that the term raises is not an endorsement of the term itself.

A related and third limitation is the restricted scope of the maker activities in this study in terms of duration and depth. The activities designed by students in the course represent short engagements of children with making akin to the introductory making and tinkering found in museums (Bevan, Gutwill, Petrich, & Wilkinson, 2015; Gutwill et al., 2015). Future research should explore the design and implementation of longer and gradually complex maker activities for children with disabilities that mirror current trends to design robust maker curricula for both informal and formal learning contexts (Bevan et al., 2015; Fields, Kafai, Nakajima, & Goode, 2017).

7. Conclusion

As the scholarship on making and learning grows, we think it is important to put an emphasis on equity, especially for children with disabilities. We posit that one way to promote a more inclusive maker movement is to teach university students how to design accessible solutions for making. In this paper, we shared the iterative design, implementation and evaluation of a university level course on accessibility in making for people with disabilities. Results from student projects show that students can learn about making and design accessibility solutions in the form of technological tools and maker activities. Moreover, students' design processes and learning improved when working with external stakeholders. This work invites researchers and practitioners of making to advance the inclusion of children with disabilities in the promises of the maker movement.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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