Towards a Social Justice Aligned Makerspace: Co-designing Custom Assistive Technology within a University Ecosystem

Erin Higgins
erinh2@umbc.edu
University of Maryland, Baltimore County
USA

Zaria Oliver
zoliver1@umbc.edu
University of Maryland, Baltimore County
USA

Foad Hamidi
foadhamidid@umbc.edu
University of Maryland, Baltimore County
USA

ABSTRACT

Digital fabrication methods offer exciting opportunities for producing customized assistive technology (AT). However, utilizing these tools currently requires a high level of technical expertise as well as time and money investments. Furthermore, facilitating collaboration between end users and makers needs effective and inclusive approaches with shared language and support for asynchronous, dispersed communication of design requirements. While these Do-It-Yourself (DIY) approaches are shown to support end-user agency and furthering technology democratization, research has to yet explore how they can further align with social justice values and practices. We explored these possibilities by facilitating DIY-AT design with students with disabilities within a university makerspace. By explicitly encouraging participants to consider social justice issues important to them as they engaged in DIY-AT design, we studied the considerations and supports needed for facilitating flexible co-design activities and broader conversations about accessibility barriers at the university. Adopting a transdisciplinary approach, we offer lessons learned about the potential of co-designing DIY-ATs as a way to investigate questions of social justice, inclusion, and access in academic contexts.

CCS CONCEPTS

• **Human-centered computing** → **Accessibility**.

KEYWORDS

3D printing, assistive technology, makerspaces, higher education, digital fabrication

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1 INTRODUCTION

Designers, researchers, and members of community organizations have worked towards utilizing digital fabrication tools (e.g., 3D printers) to create highly customized AT, also known as Do-It-Yourself AT (DIY-AT), both to address high assistive technology (AT) abandonment rates [45], and to include users in the design of their own AT [31]. Previous research has shown that these efforts have been successful in resulting in innovative AT designs [8, 24, 40, 41], and that participation in the process supports users' empowerment and creative expression [31, 34]. Furthermore, these outcomes are in line with initiatives for incorporating social justice values into the work done in makerspaces [12]. However, common fabrication technologies, such as 3D printing and modeling, are often inaccessible, costly, and time-consuming which limits the democratizing potential of makerspaces. Also, while collaborations between multiple stakeholders can address the need for technical and medical expertise, effective communication among people with different skills and experiences remains challenging [8, 24, 40, 44]. Therefore, more research is needed to make digital fabrication tools and DIY-AT design processes more accessible to individuals with disabilities to further social justice values in DIY-AT practices. We also need to find more effective and inclusive ways for multiple experts (e.g., makers, clinicians, and people with disabilities) to collaborate, iterate, and communicate together about their visions and goals for AT development.

University settings, by virtue of often having multiple digital fabrication and clinical experts in training as well as a population of students with disabilities, provide exciting opportunities for creating and refining interdisciplinary collaborative processes for creating DIY-ATs [24]. Furthermore, universities also provide underexplored opportunities for engaging social justice-oriented student groups with lived experiences of encountering and challenging complex and multifaceted barriers to accessing learning experiences. These opportunities can contribute to ongoing efforts to create equity-based approaches to making and digital design [12, 54], developing makerspaces as third spaces where people can engage in civic life [52], and work towards transforming design sites into feminist, antiracist spaces that are not only inclusive, but also organized to explicitly challenge, rather than reproduce, oppressive systems through encouraging discussion of social justice movements [12].

Motivated by this previous work, we seek to investigate the following research questions:

(1) What communication and creative supports are needed to facilitate the co-design of customized DIY-ATs with students with disabilities in a university makerspace?

(2) How can the DIY-AT co-design process engage with multiple social justice issues by generating artifacts and knowledge that respond to formal AT design and access processes?

We investigated these questions through a qualitative study with three students with disabilities from our university and one medical professional who had experience working within a university setting. We conducted pre- and post-interviews with each participant and conducted co-design sessions where we worked with them to create their own DIY-AT design. We aligned our DIY-AT design process with social justice efforts by (1) connecting to and recruiting from a student organization focused on social justice issues, and (2) explicitly inviting participants to consider and share with us not only DIY-AT design ideas but also broader experiences of inequity and oppression at the university and beyond. During the pre-interviews we asked questions regarding personal experiences with technology or systematic barriers, which led to discussion of issues with accommodations within the university, in addition to their previous experiences with digital fabrication, and their current AT use.

In this paper, we contribute to knowledge on how to facilitate DIY-AT co-design processes in a university makerspace setting by offering multiple ways of communication and creative expressions, using inclusive, non-technical language when developing relationships with multiple stakeholders, and easing the process of iteration. We further describe how university makerspaces can move towards being more aligned with social justice values by collaborating with students and university community members with lived experiences, and using the design process as a way to interrogate and subvert inequitable and inflexible formal policies and procedures.

In the following sections, we will first contextualize our study using previous research on university accommodations, research on designing with and for people with disabilities, and the use of digital fabrication tools for designing custom AT. We then describe the data collection and analysis procedures. Next, we report findings from our study as well as a description of each design process as undertaken by the participants. We conclude with a discussion of the participants' experiences with on-campus accommodations and the design of their DIY-AT as well as suggestions for the future development of university makerspaces as sites of DIY-AT design.

2 RELATED WORK

Our work builds on the existing body of research that has explored the possibilities and challenges of using digital fabrication processes (e.g., 3D printing) for AT development and customization. In this section, we provide an overview of this previous research, including work on AT and accommodations within the university setting, education surrounding designing AT, studies of DIY-AT design, and work regarding developing equitable makerspaces.

2.1 Digital Fabrication for AT Development

Previous research has shown that consumer-grade fabrication methods (e.g., 3D printing) can be leveraged to create customized assistive technologies (ATs) [8, 19, 21, 24, 27–29, 35, 40, 41, 48]. Specifically, these studies have offered methods for ecosystems of makers, clinical professionals, and people with disabilities can share knowledge [27, 48], mitigate risk [35], and create AT that responds to intersectional elements of an individual's identity (e.g., race and disability by printing AT with specific skin tones [28]). Despite this, the research also identified that current fabrication tools and processes are not inclusive of people without prior technical expertise and that without stakeholder involvement at all levels of fabrication, design, and implementation, important challenges in integrating these techniques into therapy and medicine remain [8, 24, 30, 40]. Studies in DIY-AT design have also happened outside of the medical context [4, 13, 26, 47]. It is shown that this process supports end user self-expression [4, 47], works to expand the definition of "assistive" technology and accelerate innovation [5], shows the importance of diverse and inclusive materiality for prototyping and design [13, 26], and highlights conversations around collaboration and how labor is valued [13].

In the last few decades, several online communities of makers interested in creating customized ATs have formed [8, 44, 48]. There have been successful outcomes within these communities, but previous research has also shown accessibility barriers for people with disabilities participating in online communities [8], and a tension between the priorities of hobbyists and makers and those of clinicians and therapists [25]. In particular, makers seem to prioritize "help where you can," while clinicians are guided by the principle of "do no harm." These issues motivate research to study co-design processes where these approaches can be better reconciled and balanced.

Several efforts have focused on supporting DIY-AT co-design efforts in university settings. For example, studies investigated educating PT students in 3D printing to enable them to create custom 3D printed solutions [16, 41]. These efforts showed that it is difficult to adequately teach PT students the CAD skills required to create DIY-AT devices. A follow-up study connected PT students, makers in the community, and people with disabilities to create custom DIY-AT within the context of a PT classroom [24]. The motivation was to leverage the skills of each stakeholder in order to reduce the amount of knowledge needed outside of their own domain. This approach proved to be effective in that the PT students could focus on designing functional and safe devices, while makers supported the fabrication process. However, the iterative nature of digital fabrication was difficult to implement within a formal context, which led to end users not providing as much feedback as would be expected when co-designing custom AT. The researchers also found that the asynchronous nature of the collaboration and lack of opportunities for makers and PT students to meet in person and share a deep understanding of each other's expertise led to communication challenges through the process, as well [24].

This previous research shows the need for creating accessible digital fabrication tools and processes. Furthermore, there is a need to develop innovative interdisciplinary approaches to bring together multiple experts (makers, clinicians, and people with disabilities) to easily collaborate, iterate, and communicate about their DIY-AT needs and goals. In this project, we build on previous research to better understand what is needed to facilitate the co-design of low-risk, customized AT in a university makerspace. We thus explore the potential of the university makerspace as a site to invite collaboration between students with disabilities, medical and other professionals within the university, and other students with unique expertise (e.g., digital fabrication, mechanical engineering, etc.) and to use the process as a way to investigate broader questions related to accessibility, inclusion, and social justice.

2.2 Accommodations within the university setting

In the United States under section 504 of the Rehabilitation Act legislation, there are two components needed for a student to receive accommodations within the university setting: self-identification of disability and request for accommodations [43]. Research has shown that universities follow either medical or individual models of disability as opposed to social or universal models for documentation requirements [6, 17]. This means that universities are focused on the individual medical condition rather than the social and structural barriers experienced by students with a disability. Specific documentation can be hard for students to receive due to these structural barriers and, in addition, staff may not have the resources or knowledge to address students' academic requirements in a way that leverages the students' strengths [10]. It is also often only privileged students who are able to have a diagnosis that the university has appropriate accommodations for or considers for the accommodation process [36, 39]. The policies and attitudes ascribed to disability within a university directly impact students' ability to succeed in school and belief in their ability to complete graduate education [51]. For accommodations to work for the maximum amount of students, they need to be flexible and provide multiple options [32, 37, 38]. This level of flexibility and uniqueness for each student is often at odds with the policies and attitudes held by the university.

Disability activism on university campuses has been used as one way of gaining access to accommodations in this setting. Students are often required to act as activists and self-advocate as a means to accessing accommodations within universities [33]. Placing this responsibility on students with disabilities is problematic, however, and working towards meaningful access requires building mechanisms for accountability that are able to question ableist cultures that are often found in higher education spaces rather than focusing on logistics [22]. Deep work around applying a social justice approach to disability in higher education relies on the assumption that barriers to success are found in the structural, organizational, physical, and attitudinal aspects of universities and structural change is demanded in order to truly provide inclusive access at the university level [15].

Not only do students face issues receiving accommodations from a policy standpoint, but many assistive technology users feel that using AT in public spaces (such as a university setting) makes their disabilities more obvious and draws attention to them [50]. This can lead to misconceptions from others, such as AT eliminating a user's disability or the user being unable to do anything without these technologies [50]. AT making and self-adaptations can help individuals to define their own identities [5] and represent a way to rebel against traditional expert led-design approaches [23]. Overall, it has been suggested that aligning making with social justice initiatives would remove some of the identified issues within the university setting.

2.3 University students designing for and with people with disabilities

Previous research has identified ways that university students in technical programs (e.g., computer science, information systems, etc.) can learn about accessibility and assistive technologies as part of their education [3, 56]. For example, previous research has shown that to truly increase students' understanding of designing for people with disabilities, their courses must include design sessions with people with disabilities alongside individuals who do not identify as having a disability (e.g., [9]). This has been shown to improve student learning of accessible design processes and increase their understanding that people with the same disabilities can have different needs while people without disabilities might have the same needs as people with disabilities [49]. Furthermore, they can help with educating students about the importance of considering social aspects of assistive technology and accessibility design [50].

These recommendations are in line with Ladner's call for making user empowerment a priority in these contexts [34]. Ladner emphasized the importance of designers working with people with disabilities in order to achieve usable and relevant designs [34]. Furthermore, he stresses that it is even better to empower people with disabilities to design and build the technologies themselves, and identifies two important features that allow for this: self-determination and technical expertise [34]. To achieve these goals, efforts require creating accessible design and fabrication tools and processes to ensure that people with disabilities, including students, can participate in designing technologies both at the university setting and beyond [9, 18, 31, 55].

2.4 Towards equity in makerspaces

Though makerspaces have the potential to support the democratization of AT development [24, 25, 40], research has shown that historically these spaces are often not inclusive and can recreate systems of oppression [12, 54]. For example, Vossoughi et al. argued that to move towards equity in makerspaces, sociopolitical inquiry into the politics and capitalistic practices prevalent in maker culture is required [54]. Research has explored ways to support the development of makerspaces as a third space where people can engage in civic life [52] and found that spaces that reach out and respond to their communities are more successful in becoming more equitable and inclusive. Some work pushes this concept further and works towards aligning design justice with feminism and racial justice [12]. Costanza-Chock argues that design sites should be transformed into feminist, antiracist spaces that are not only inclusive but also organized to explicitly challenge rather than reproduce oppressive systems. They further identify aligning with social justice movements, ensuring community voices are given authority, and removing financial barriers as practical tactics for moving towards this goal [12].

3 METHODS

We used interviews and co-design sessions to investigate our research questions. Three students with disabilities from our university and one medical professional with experience as an audiologist within another local university setting participated in the study.

Each participant completed three activities split between two sessions: an initial interview and a co-design session to create a DIY-AT for themselves (Session 1), and a follow-up interview after their device was printed (Session 2). Each participant received 25 dollars for each session (50 dollars total). Our study procedures were reviewed and approved by our university's institutional ethics board (IRB) before data collection.

3.1 Participants

Three undergraduate university students with disabilities and one medical professional participated in this study. Their relevant information, including a description of what they chose to design, is shown below. Given the small number of participants, we considered using pseudonyms to refer to each. However, we had not anticipated this before the study and did not ask participants to suggest pseudonyms themselves, which is recommended by previous research[2]. Therefore, we decided to use participant numbers instead.

3.1.1 Participant 1.

Background and Demographics. P1 is a 32 year old woman who is majoring in gender and sexuality studies as well as political science at our university. She started and is the president of the disability advocacy union on campus. She develops and hosts a wide variety of disability advocacy focused events on campus. This participant chose to disclose that their disability involves hyper mobility of their joints which she wished to address with her design.

Recruitment. P1 was recruited after the first author was asked to present to their newly forming student advocacy organization about 3D printed AT. The presentation sparked a natural interest in trying the process of DIY-AT for herself.

Prototype and Iteration Process. P1 decided to create a finger splint to prevent over-extension of her fingers. She iterated on this design by providing example products and then received physical, 3D-printed versions of the provided examples. She then commented on those physical prototypes and they were changed according to her specifications. The tools used for iteration were in-person conversations and research team generated sketches. This participant has the technical skill needed to learn CAD skills but did not have interest in learning them.

3.1.2 Participant 2.

Background and Demographics. P2 is a 26 year old woman who is majoring in visual arts and photography at our university. She is also an activist on campus and deeply involved with the disability advocacy union. This participant chose to disclose that their disability involves dysgraphia and fibromyalgia that causes her to use a wheelchair regularly.

Recruitment. This participant was found through snowball sampling through P1 as a result of their involvement with activism organizations on campus.

Prototype and Iteration Process. P2 chose to create a custom-fitted pencil grip to prevent pain when writing or drawing for longer periods of time while working towards their art degree. This accommodation was not provided by the university. To iterate on this device the participant used clay modeling, sketches, email, and in-person conversation. This participant has the technical skill needed to learn CAD skills but did not have interest in learning them.

3.1.3 Participant 3.

Background and Demographics. P3 is a 20 year old man who is majoring in computer science at our university. He was not a part of the advocacy group on campus. This participant chose to disclose that their cerebral palsy prevents them from using their left hand for most tasks, including typing.

Recruitment. Unlike the previous two participants, he was recruited after joining our lab as a volunteer to gain research experience and is not involved in advocacy work explicitly on campus.

Prototype and Iteration Process. P3 chose to create a turn signal extender to ease the process of signaling a turn in his car while driving. This had been suggested to him by a medical professional. This student, unlike the others involved in this process, wanted to create the device himself. He returned for three extra sessions where he was taught the basics of CAD and he designed his device himself. He printed and iterated on the design personally with guidance from the research team.

3.1.4 Participant 4.

Background and Demographics. P4 is a 52 year old audiologist who has experience working in a university setting. She is a black woman who works in a field in which 3D printing is used to create nearly all of the devices they prescribe. The 3D printing is not done at their medical office, however, and is outsourced to a company that does not provide much opportunity for customization.

Recruitment. P4 is the mother of the second author. She asked to participate in this study after discussing the project in detail with her daughter.

Prototype and Iteration Process. P4 chose to create a bone conduction headband to attach to a headset that would match the color and texture of her natural hair. Though she expressed interest in learning these skills herself, she felt she did not currently have the time to commit to designing and printing herself. She used in-person conversations and sketches to communicate and iterate on her design.

3.2 Data collection

3.2.1 Semi-structured Interviews with participants. The pre-interview was conducted before the co-design activity. It was conducted as a semi-structured interview to understand each participant's previous experience with 3D printing-related technologies (e.g., computers, 3D modeling software, 3D printers), their general strategies for solving technical problems, their current AT usage, their experience with or knowledge of DIY-AT, and their experience with accessibility accommodations offered by their university. They were then given a brief overview of the 3D printing process, including design software and printing, and asked about their accessibility concerns, interest in learning the technology, and ideas for applications. In an effort to work towards creating a feminist, antiracist space, as outlined in [12], individuals were encouraged to share their experience having a disability in a university setting, discuss their advocacy work, and connect these ideas to the work we were doing in the makerspace. The interviews lasted 26 minutes on average.

After the product was designed and printed, the participants returned for a post interview. This was another semi-structured interview that began by eliciting feedback on their printed device to decide on any changes that needed to be made. From there, we asked about their opinions on DIY-AT and if they saw value in the iterative process. Finally, we asked about their opinions of 3D printing, if they thought it would be a reasonable task to do alone, and what possibilities and limitations they saw with the process. These interviews also lasted 26 minutes on average.

3.2.2 Co-design sessions. After the initial interview, all participants took part in co-design activities with a member of the research team. The pre-interview and co-design took place in the same session. The design sessions were led by each participant. During the design activities, participants worked with the researchers to brainstorm design ideas, decide on a final design and then used different methods to communicate their design with the researcher. They could either design the AT themselves or communicate and discuss the idea with a member of the research team who would then fabricate a prototype that they would collaboratively iterate on through end-user feedback. We provided multiple options for communicating designs in accordance with recommendations from previous research on DIY-AT design with multiple stakeholders [24]. Participants communicated using drawings, 3D modeling, providing example products, or verbally discussing their ideas. Multiple modes of communication were used as suggested in [24]. Participants were informed in in advance that they would be developing a personal AT device and could bring an idea to workshop with the researchers. The researchers provided feedback on suggested ideas and guided the participants away from any item that could potentially injure them. One participant expressed interest in learning tinkerCAD. They returned for 3 entry level 3D modeling instruction sessions in which they developed their own AT using CAD tools. The first session was an introduction to basic tinkerCAD functionality. The second session was around finding an example project to start from and starting to adjust it to their specifications. The final session revolved around changing measurements according to their specific situation. All other participants had the research team produce the CAD files and offered asynchronous feedback over email or in-person.

3.3 Data analysis

Each interview and design session was audio recorded and transcribed by the first author. We then conducted thematic analysis, using an inductive approach where we developed themes based on participant input [7]. To complete this process, the first author coded the first interview using open coding. She then discussed the codes with the second author before the other interviews were coded with open coding. An informal peer review was done at this point to solicit feedback on the themes. Finally, both researchers had discussions about the data and the first author developed themes using axial and selective coding. Paper and photo documentation of the DIY-AT prototypes were consulted to contextualize the interview and design session data.

3.4 Research team positionality

The research team worked closely with the students and medical professional in order to develop these DIY-AT products. The research team consists of one faculty and two student researchers, including Caucasian and Black members as well as two females. The first author who led and conducted most of the data collection and analysis activities is a PhD student with a master's degree in rehabilitation science. She is a white woman who does not identify as having a disability. She has done research alongside people with disabilities for eight years and has some clinical experience as an assistive technology professional (ATP). Our lab is situated in a minority-serving institution in the United States, with more than half the students identifying as people of color. The majority of the research projects in the our lab are focused on issues at the intersection of social and environmental justice.

4 FINDINGS

Our findings consisted of device design outcomes and student feedback on their experience with designing and creating their own DIY-AT. We will first present the four devices as designed by the participants followed by findings from our interviews that shed light on barriers they face in creating DIY-ATs, their feedback on our iterative design process, and the potential for empowerment and inclusion as motivators for creating DIY-ATs. We will conclude by presenting participants' input about the challenges of interacting with formal university accommodation systems, which they brought up as an exemplar and relevant social justice issue facing students with disabilities in the academic context.

4.1 Co-designed DIY-AT Devices

At the conclusion of the co-design process, all four participants had each created a 3D printed device that they were able to use. Below, we describe each device and the process of creating them.

Device 1 was created by Participant 1 and was a finger splint to prevent over extension of her finger due to hyper mobility in her joints. Participant 1 provided the design team with a pre-fabricated finger splint that she currently used as a physical model to create Device 1. We created a 3D model of the design based on the physical device using tinkerCAD and printed as shown in Figure 1. This finger splint is not covered as an accommodation within the university, as it is not considered directly related to the student's ability to perform school-related tasks. It is also not covered by insurance for this participant and many others. The student shared that they decided to create this device to avoid the high out-of-pocket cost of purchasing the pre-fabricated version, since it is not covered by insurance. We iterated on the device's design twice before the participant was satisfied with the final product.

When asked about the need for iterative design and multiple meetings to refine DIY-AT, the participants indicated that these requirements would not deter them if making is done within the university setting (rather than another location). When asked about her opinions on the iteration required, Participant 1 compared them with other methods of acquiring AT and stated, *"Keep in mind, ring* *splints are almost always iterative in general. So… if they order the silver ring brands, which are very expensive, the processing time on them is insane. And then you have a 50 percent chance that they're not going to fit because the measuring system is not great… Ones like these are both realistically somewhat simple compared to some of the other options out there that people are trying to get. And they're still getting the wrong product. So, in terms of the time spent of doing an iterative 3D printing, it's probably the same but you would get a better outcome at the end, in my opinion."* These comments show that while iteration can be time-consuming, Participant 1 saw the value in the process and identified the benefits of supporting DIY-AT making in the university setting.

Participant 2 chose to design a custom pencil grip (Device 2) to assist in her classes that required her to draw. Participant 2 used clay to communicate their idea for Device 2, which is shown in Figure 2. This participant chose to create this particular device for use while drawing. As an art major, she spends a considerable amount of time drawing for her classes. She explained that this causes pain in her hands due to dysgraphia and fibromyalgia and that the grip would help to keep her hand in a more relaxed position. After the participant created the clay model, we scanned it with an iPhone application called PolyCam and printed as seen in Figure 2. After the team developed the CAD model, it was sent to P2 over email for their feedback but no feedback was provided during this step of the process. Participant 2 explained, *"I got kind of discouraged when I saw this lumpy weird thing in an email… But this [the printed device] was actually a similar concept and having this in my hands, I like this a lot, I would use this."* They expressed that a CAD image was confusing to them over email because they couldn't get a sense for what it would look like when printed at all. When asked what some digital communication alternatives, Participant 2 stated, *"I do think it's basically necessary to have the prototypes in my hand to work from there. It gives me a starting point to communicate exactly where I want to go with it… It's definitely easier to be like, 'Okay, I have this. This is what I want to change.'"* This participant, as well as the other two student participants expressed that physically touching the material changed their understanding of 3D printed devices. They felt that physically interacting with the item was the best way to communicate about the iteration process. The participant was happy with the first printed iteration of the device and asked for two more variations: one that could accommodate pens as well as another with no hanging grip for use in a different style of art.

Device 3 was a turn signal extender for use by Participant 3 while driving. Participant 3 wanted to 3D model the design himself and started by taking a photo of his car's turn signal switch and augmented it with two colored pens. He also made measurements in his car and combined these two initial designs in tinkerCAD as a 3D model of his device, as shown in Figure 3. Due to cerebral palsy, this participant has difficulty with left-hand movements. This makes it difficult to put on the turn signal while driving. His physical therapist had previously suggested attaching a pencil with tape to the turn signal, but the participant felt a customized 3D printed device would be safer to use. He printed the device himself and iterated on it one time to make it more stable after breaking it during a test drive in his car. The physicality of the device also helped P3 to understand the potential of 3D printing and increase their appreciation for the process and they stated, *"It was cool to learn the 3D printing and it actually turned out a lot better than I expected. My view of 3D printing was that it comes out kind of like brittle or not too strong, but this is solid. It seems like it has some strength and some durability to it that I wasn't really expecting. So that's really awesome."* Going through this process increased P3's optimism about 3D printing.

Device 4 is a bone conduction headband designed to match Participant 4's hair. Participant 4 verbally described their idea while the second author sketched their idea. This led to the sketch of Device 4 as seen in Figure 4. This medical professional decided to design this headband to look their her own hair in an effort to draw less attention to the hearing device. The device needed to be iterated upon one time to fix the hooks that attached the headband to the hearing device.

All participants expressed that once they saw, touched, and interacted with the devices, they were surprised at how well they had turned out, making them hopeful for the success of similar processes in the future.

4.2 Barriers to students creating DIY-AT

Though all participants were excited to participate in the DIY-AT co-design activity, they identified several barriers that might prevent the participation of more students with disabilities in similar activities. One of the biggest barriers was that many students with disabilities do not have a relationship to a medical professional who would help them with designing and customizing devices. Referring to students with invisible disabilities (e.g., non-visible and generally cognitive disabilities), Participant 1 stated, *"We're talking about students who are struggling to even get doctors to take them seriously and get a diagnosis. They're light years away from where I am, where I have a physical therapist that I've worked with for two years who I can ask like, 'What do you think?' and get ideas and suggestions."* This participant directly worked with her physical therapist to come up with ideas for this project and feels that was important to the safe and appropriate selection of a DIY-AT project for digital fabrication. Participant 1 went on to explain that in terms of getting students involved, *"… it's not as clear cut as just them being interested because someone can say, 'Well, yeah that would be cool, but I have zero clue medically what I would need."* Participant 1 felt strongly that students who didn't have confidence in their knowledge of their own disability through a relationship with a medical professional would be hesitant to design something for themselves. Participant 4, who is a medical professional, took this a step further and explained that it would even be "risky" to design certain medical items without this relationship.

Another barrier identified by the participants was the language used to inform the students about this project. On the flyer created by the research team, the term DIY-AT was used. Participant 1 expressed that this wording might make people hesitant to participate because they don't understand that they will only have to do as much as they are comfortable with. Even though the flyer directly stated that no experience or interest in the process was needed, she expressed that just having DIY on it was enough to deter students. She explained, *"Language is really important to some of our groups in a way that it's not going to be if you're working with an able population. And that's something that I'm learning and working with*

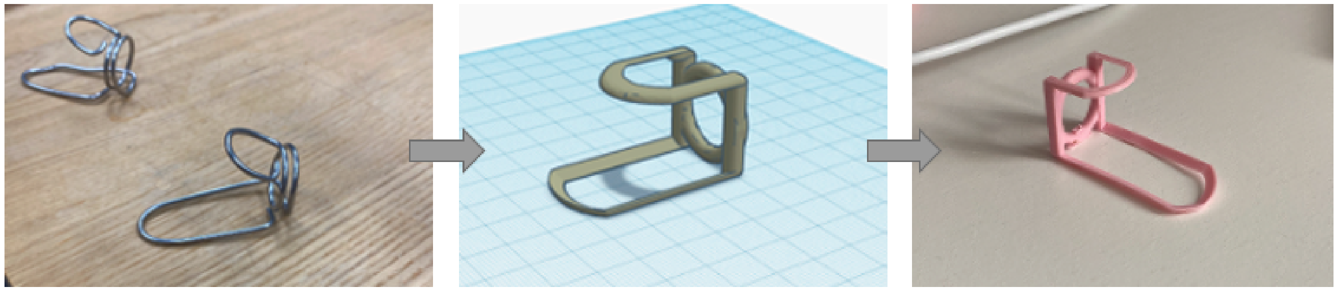

Figure 1: Design process for Device 1 - Finger Splint: The image on the left shows a mass-produced device that was used to model the customized version. The middle image shows a 3D model of the device created in the tinkerCAD 3D modeling software. The image on the right, shows the final 3D printed object.

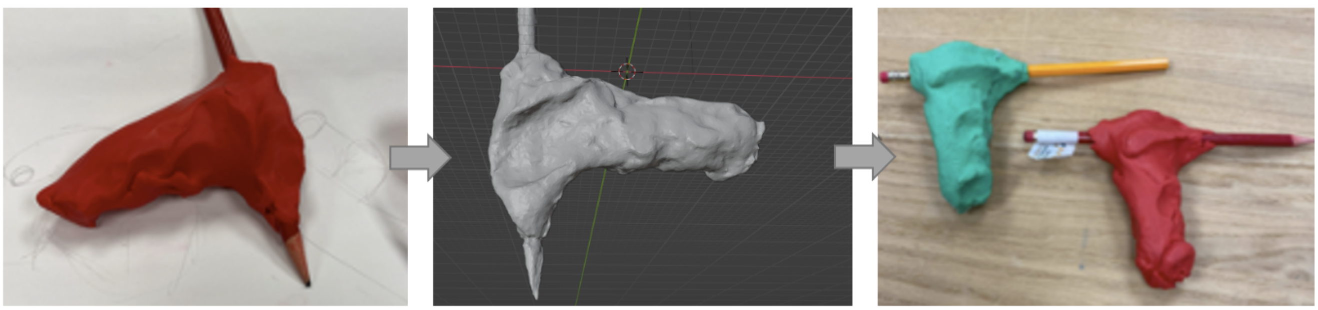

Figure 2: Design process for Device 2 - Custom Pencil Grip: The leftmost image shows a clay model of the device as created by the participant by slowly molding clay to fit their hand and accommodate a pencil. The middle image shows the .stl file that was generated by scanning the clay model with the Polycam application. Finally, the rightmost image shows the printed model (green) next to the clay model (red).

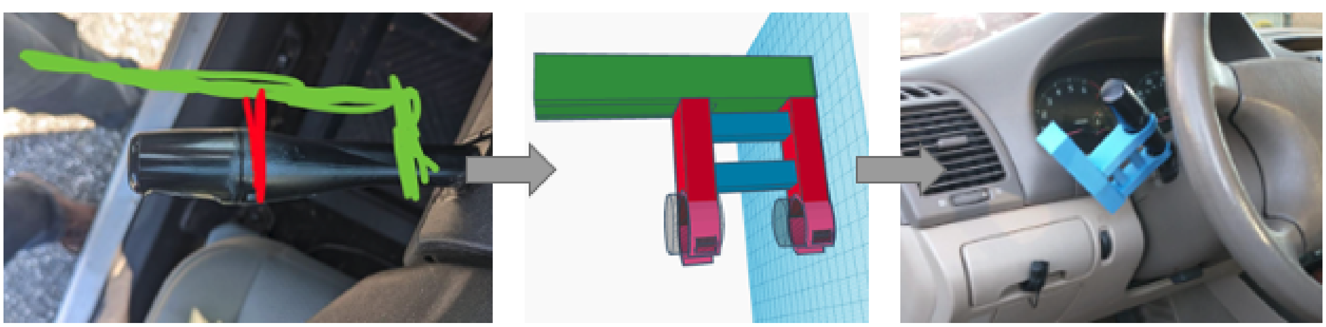

Figure 3: Design process for Device 3 - Turn signal switch extender: The leftmost image shows a sketch over a photo of a turn signal that was drawn by the participant. The middle image shows the sketched device in tinkerCAD. Finally, the rightmost image shows the printed device attached to the participant's car.

myself, in trying to lead this group, is sometimes the way that I have worded things will make somebody not interested in participating, even if my intent would have interest them." Participant 1 expresses that in order to get more students involved with the process of making their own AT, they would need very clear language and an understanding of what would be involved in the process. Otherwise, the process might not reach individuals who would benefit the most from it.

The final barrier to student involvement in designing DIY-AT is a general lack of knowledge about the resources provided at the university. When interviewing Participant 2, she stated that if there was a 3D printer in the commons building on campus more people would print their own things. However, there is already a 3D printer

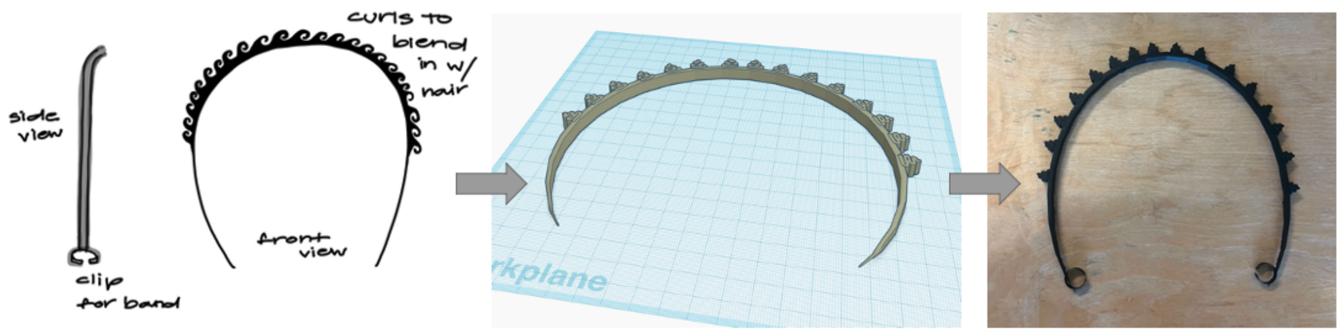

Figure 4: Design process for Device 4 - Bone conduction headband: The leftmost image shows a sketch on paper with notes generated in the initial design session. The middle image shows the sketch recreated in tinkerCAD. Finally, the rightmost image shows the printed device on a table.

that is available for public use in that building, and the issue seems to be that information about this resource is not easy to find for students. Despite working in digital fabrication at the university as part of her research, even the first author did not know about this 3D printer at the time of the interview. Participant 4 also stated that medical students need to work with patients on campus to complete their degrees in most cases. However, there does not seem to be a clear connection between different departments to communicate available resources and expertise in each area.

4.3 Empowerment and inclusion as motivators for DIY-AT creation

Though everyone expressed excitement about the potential of 3D printing for them or their profession, each participant expressed unique motivations for why it could be impactful for them. Participant 1 expressed that their motivation was around the economic benefits of 3D printing. When they learned that the printer used to print her device cost 150 dollars, she was extremely surprised as that is less money than one pair of her current finger splints. She explained, *"I'm not super interested in like necessarily doing it [3D printing] from a hobby or creative standpoint, but I could definitely see that I may choose to learn it from an economic standpoint."* Though this participant initially had no interest in participating in the design process for this project, seeing the results made her reconsider learning this skill for economic reasons. She didn't just think about her personal economics, however, and felt that many people could benefit. She explained, *"If you're able to perfect this [design], I could probably put this on Twitter and a ton of people would be looking into, 'How do I print these for myself?'"* Participant 1 saw the potential of this technology to subvert some of the expensive and prohibitive AT practices that currently exist for herself as well as for her community, and was interested in using social media to share her design and experience as a potential way to reduce costs and increase access to AT.

In contrast, rather than having their own 3D printer to create DIY-AT, Participant 2 preferred to use similar services in the future to benefit from shared resources and skills. She expressed, *"I certainly could do that myself, but you know that equipment and materials are such a big upfront cost. And I don't think I'm interested enough to do all of it myself if I know printers and other people who can operate them are available to me."* While Participant 2 sees the benefit and potential of 3D printing, she is happy to leverage opportunities that may be afforded to her by having access to a university makerspace instead of learning skills that she isn't interested in or putting money towards equipment that she may be able to access as a shared resource.

Participant 3 did not mention the economics of AT. His motivation stemmed from the sense of empowerment and satisfaction experienced from going through this process. He explained, *"It's kind of cool to be like 'Not only did I fix this thing, but I made the thing that I fixed it with.' So, it kind of brings some satisfaction that you're doing it yourself."* This expression of empowerment and skill development motivated this participant to continue developing and designing DIY-AT.

The final motivator, as expressed by the medical professional (Participant 4) was supporting inclusion through design. When working as an audiologist, Participant 4 expressed frustration that they were limited in their options of creating hearing aid skin tones to those that match the skin tones of white and light-skinned users. She stated, *"Nothing is the flesh tone. With me being an African American, myself, what can I do? 'Does it have to be pink?' That's what they [her patients] say. 'Why does it have to be pink, I'm not that color. Can they do my color?' and I'm like 'They can't do your color.'"* This participant offered a unique perspective that 3D printing may support more inclusive aesthetics for AT. Her own printed device (shown in Figure 4) was a headband to connect to her bone connection headphones that would match the color and texture of her natural hair. Despite her excitement, she also stated that while 3D printing is popular in her profession, they only use outsourced fabricators who do not make custom colors or styles. When asked if she could envision audiologists printing their own solutions, she stated, *"I would say unlikely. I would probably, but because of the demand. . . each day for an audiologist is so busy with testing and counseling. . . that's something that will likely have to be done after hours."* The time constraints of her profession led her to believe that audiologists would not have the time to make custom devices for their patients. She expressed that she felt the best way for this to become a reality would be for a person to have a relationship with a medical professional to assist them in fitting and then printing on their own time, a process similar to what we employed with the student participants.

4.4 Barriers to receiving appropriate university accommodations

When asked about accessibility and inclusion challenges they experience or are aware of in the university context, all participants expressed that university accommodation systems were confusing and often biased towards serving students with visible disabilities, and privileging those who have official medical documentation. As Participant 1 expressed, *"Students with non-physical disabilities are discriminated against and stigmatized at this university. And even physical disabilities, it depends on how much documentation you can produce, which is a very privileged system."* This participant was expressing that it is often difficult to receive accommodations for non-physical cognitive disabilities. They also stressed that without specific documentation, it could also be incredibly hard to receive the appropriate accommodations. They state that this is privileged in that many people do not have the resources required to develop the needed relationship with a medical professional in order to get the proper paperwork. The student described how she was motivated to start a student advocacy organization focused on disability rights on campus with the goal of bringing some of these issues to the administration and to change discriminatory policies.

As Participant 2 explained, sometimes even with the proper documentation, students will still not receive accommodations, *"I was told on my intake that I could not have a calculator because ADD [attention deficit disorder] is not a mathematical disability…And again, I'm one of the lucky ones, I got pretty much everything else I needed...but the one I didn't get is a calculator for tests, which, in the report, the psychologist that we worked with for this evaluation, recommended due to my inefficiencies with working memories. I would love to have had a calculator for my exams when I was pretending to be a software engineer and taking calculus."* This student has a physical disability as well as non-physical disabilities. Even with the appropriate steps taken and a medical professional explaining that a calculator was a necessary accommodation for exams, they still did not receive this accommodation because in the university system, having ADD does not qualify getting a calculator during exams as an accommodation. This student eventually stopped pursuing a computer science degree and switched their major. As an art student, they still struggled with pain when drawing for extended amounts of time, as explained above. Though a custom pencil grip would not be covered under the university accommodation system due to their rigid verbiage, this device was able to be designed and printed in our makerspace to assist this student in circumventing some of these restrictive policies.

According to our participants, the tension between official medical recommendations and policy regarding accommodations within the university could also happen on the other extreme end, where students may receive too many accommodations that they do not understand. As Participant 3 explained, *"At my previous college, they gave quite an incredible amount of accommodations, really. Like they asked me a lot of questions. And then by the end of it, they said, when I take tests and stuff, I could have double time if I wanted. And I didn't really know where that came from, like the fact that I could have double time."* This participant felt that the university was providing unnecessary accommodations that he did not need based on his own understanding of his abilities. Though this seems like it might be more favorable than not receiving accommodations, Participant 2 expressed, *"I haven't actually gone through the accommodations process here because this semester I'm not taking any labs or anything. I should go through that process. But I don't know, there's something about it where I just kind of…I don't know…I don't always like the idea of having an accommodation."* Receiving unnecessary accommodations can make a student, such as Participant 3, feel uncomfortable. With his previous experience before transferring to our university, this student felt more comfortable not partaking in the accommodation process because of the discomfort he felt with receiving accommodations that he viewed as unrelated to his disability. Overall, the barriers to receiving appropriate accommodations on campus led students to resist the accommodation process, switch their major, and even start an organization to attempt to change the system within the university.

5 DISCUSSION

Our findings provide insights into the potential of moving towards a social justice-oriented university makerspace that creates a space for students with disabilities to exercise agency and creativity in designing their own ATs. We found that universities are uniquely situated to encourage these collaboration and fabrication efforts. However, the language and tools used within the process need to be improved to encourage participation and mediate communication issues. We also highlight the potential of a university makerspace, when aligned with social justice movements, to create a space for discussing accessibility and inclusion barriers and challenges specific to the university ecosystem, and to create possibilities for creative subversion and interrogation of existing systems.

5.1 Supporting the co-creation of DIY-AT at university makerspaces

Through this study, we have shown how a university makerspace can enable the creation of customized and functional DIY-AT for students with disabilities. We have also shown that it has the potential to be a facilitator for collaboration between multiple stakeholders, including clinicians, makers, and the person for whom the device is being designed. These results build on similar efforts that have shown how universities can be the site of creating DIY-AT through interdisciplinary collaborations (e.g., [14, 24, 41]). Based on our findings, we present several recommendations for setting up similar efforts.

First, we found that providing multiple ways for participants to create and communicate initial designs, such as sketches, photographs, and using existing objects as starting points, and building in time for multiple prototyping iterations, can make the design and fabrication process more inclusive to both participants with disabilities and other community members without digital fabrication experience. This recommendation aligns with the Universal Design principle of providing multiple ways of expression [1]. Our study also showed that not every student will be interested in designing their product themselves, as seen with participants 1 and 2. As seen in our study, even though the versatility in communicating about design ideas proved effective, intermediate communication about their designs (over email in this case) was confusing and made the students doubt the process. It wasn't until they were able to interact with the product in a tactile way that they had a full understanding of the materiality of what they were creating. This changed their understanding of the process and increased their engagement with 3D printing. These findings indicate that there is a need for better communication tools in this space. Another challenge with the iterative design of DIY-AT is that while printing physical versions of initial designs elicits useful feedback, as indicated by Participant 2, there is an environmental impact of using plastic in this way [53]. One potential solution would be to have a set of example prints from previous student projects to help students understand the materiality of plastic filament sooner in the process. Despite this challenge, we would like to stress that giving feedback on intermediate steps is important, and there is an opportunity to develop solutions to improve upon using emailed photos.

Another suggestion about making DIY-AT in the university ecosystem is to make university resources visible and the communication about the process of creating DIY-AT clearer. Students who participated in our study were unaware that there were 3D printers on campus (outside of our makerspace) that they could use for these purposes. Moreover, they did not have connections with other students with digital fabrication or making experience and interest to facilitate co-designing in the way that we did for this study. Making these on-campus spaces and resources more evident and clearer to students can increase the number of students who are interested in designing for themselves. However, as pointed out by Participant 1, who runs the student advocacy organization on campus, the language around these opportunities must be very clear and direct. She suggested that even the notion of "DIY" would intimidate some students with disabilities, even if they did not have to physically design anything themselves. This feedback indicates that to increase participation and create a space where students with disabilities feel comfortable and welcome, the language and communication practices also need to be co-designed and refined through iterations to improve it. In our North American context (as in many others), universities are privileged spaces. The services and resources offered through them are not available to the broader public. This is both a limitation of these organizations and a largely untapped opportunity for supporting and sharing resources with social justice-oriented community initiatives in the future.

Another recommendation is using DIY-AT making as an opportunity for setting up interdisciplinary collaborations in the university setting. Many universities, such as ours, have experts in mechanical and electrical engineering and computer science as well as access to individuals with medical and clinical backgrounds or connections. There are opportunities for drawing on these multiple and diverse expertise to support the creation and acquisition of ATs. Every participant brought up how important the relationship with a medical professional was to the proper acquisition of AT. Utilizing the campus ecosystem could provide new ways for students to receive some feedback from faculty or student clinicians-in-training while they design their own devices and which could eliminate some barriers to accommodation and AT acquisition in university settings. They also pointed to the importance of relationship-building with a medical professional. Repeated and consistent availability of medical professionals for consulting on projects was indicated by the participants to be important and could be facilitated in the university setting. Interdisciplinary collaboration is often expected and supported in academia which combined with the need for it in creating DIY-AT, makes the university a well-suited site for facilitating these processes. Encouraging this collaboration on campus will also give faculty and staff from multiple departments the ability to create devices with people with disabilities, which previous research has indicated is a necessary step for students to truly learn about accessibility and universal design [49]. Developing an ecosystem that includes stakeholders from multiple backgrounds (e.g., clinical, engineering, etc.) within the university working to develop solutions led by students with disabilities can counteract some of the limiting policies that prevent students from having access to the ATs (DIY or otherwise) that they need.

Finally, as is evident with Participant 3 and also shown in previous research [9], creating DIY-AT at the university can result in students with disabilities gaining the technical expertise and self-determination that are previously pointed to as requirements for users to develop technologies for themselves [34]. Participant feedback on the design process shows that engaging with the full design process can result in technology self-efficacy and confidence in required technical skills that can be leveraged for creating valuable learning experiences in the future. Our study focused on 3D printing as that is where our current lab's expertise lies. However, these findings can inform other maker practices, such as physical computing and interactive textiles [20, 42], which offer exciting areas for future research exploration.

5.2 University makerspaces as sites of antiracist and inclusive DIY-AT making

A key motivation for the current study was to investigate how the creation of DIY-AT can be used as an opportunity to understand multidimensional social justice issues in the university setting from diverse perspectives. To this end, we explicitly communicated with participants that we were interested in all aspects of social justice and encouraged them to share with us, through their interviews and designs, their experiences and perspectives that may go beyond the functional aspects of AT. We also engaged with a student organization focused on disability rights and culture and recruited diverse participants. We found that these strategies resulted in outcomes that touch on multiple aspects of vulnerable identity and that participants used the creation of DIY-AT as an opportunity to discuss systemic dimensions of oppression both at the university and beyond. For example, Participant 2 created a device to assist her in her coursework that was not provided by the university and Participant 4 created a device that matched the color and texture of her natural hair that a manufacturer would never provide. These two devices explicitly interrogate the restrictive and non-inclusive process of AT design and procurement.

The students who participated in this study all expressed challenges faced when dealing with the accommodation process within the university. They indicated that it is a privileged system, in that it prioritizes students with official documentation and well-known and visible disabilities. They also shared that even when a student has proper documentation, the accommodations received might mistmatch their needs and be too much or too little. Many of these issues echoes findings from previous research by Tamjeed et al. [51] who showed that the lack of AT and accommodations is an important factor in student's perceptions of their own ability to complete schooling. Given the material and time costs of maintaining an ongoing relationship with a medical professional, this need for formal documentation to receive university accommodations, signals an under-explored experience of vulnerability at the intersection of disability and socioeconomic status [11, 46].

Participant 1 noted that she saw the potential of digital fabrication to allow her and members of her community to circumvent the oppressive costs and burden of acquisition that AT in the university setting could present to them. She saw digital fabrication as an economical alternative that could allow people without resources to share amongst their community and make for each other. This subversion of capitalistic AT procurement and unfair university policies were directly in line with what Participants 1 and 2 were advocating for in their activism work on campus. We find the connection between DIY-AT making and broader social justice issues that involve questioning traditional capitalistic processes promising in informing how our future efforts in the makerspace can better align with the goals of design justice and equity as indicated by [12, 52, 54].

Our findings show that there is much potential in using AT co-design as a productive way to bring together like-minded people to generate discussion and increase awareness and solidarity, which may ultimately bring about change. Furthermore, artifacts created using AT co-design may serve as exemplars that encapsulate critical perspectives on the existing status quo. While not all designs or perspectives were explicitly critical, we believe that these findings point to productive directions for better aligning making, and DIY-AT making in particular, with social justice values, such as antiracism and radical inclusion that can empower students with disabilities, not only by generating devices, but by providing new ways of interrogating larger power structures (e.g., the university system) through creative practices.

Activism is demanded of all members of a campus community, but especially those with disabilities, in order to increase access [15, 22, 33]. Makerspace-created AT can work to support activism and provide tangible artifacts to critique the inequitable power structures at play within the university system. Both the making and accessibility movements revolve around empowerment. Both movements are rooted in creativity and subvert the traditional systems put in place around the acquisition of technology. The intersectional elements of accessibility and making provide an inherent connection that can be leveraged, as shown with our study, to create technology that is in itself critical of the systems that have previously prevented the acquisition of these needed ATs.

6 LIMITATIONS AND FUTURE WORK

We would like to continue our work to understand the long-term possibilities of aligning research facilities and makerspaces with the social justice efforts of students and community members. We would like to work with more participants to confirm our findings and continue working towards our goals of creating an antiracist, feminist makerspace within the university ecosystem. As this paper presents a series of case studies, we make no claims that this is a representative sample, rather this paper serves to present a novel lens to view the co-design process and framing for makerspace activities in this context.

Our university's context and characteristics (e.g., being a minority-serving research-intensive US institution, among others) impact our study design and outcomes, and we would like to replicate our approach in other contexts to better understand how our findings can transfer to new settings. On a related note, the particular resources, processes, and expertise at our site impact our outcomes, and future studies can assess these impacts through comparative research.

In the future, we would like to implement our lessons learned, and in particular, include perspectives from university accessibility services to see how our work can better complement each other. We would then study the makerspace and resulting ecosystem of experts to explore the challenges and possibilities of aligning social justice and grassroots approaches with formal infrastructure and support.

7 CONCLUSIONS

Our study has contributed to a better understanding of the potential of university contexts for bringing together diverse groups of stakeholders, including students with disabilities, to co-design DIY-AT and discuss accessibility barriers and gaps. Our study has also shown how co-design activities can create space to discuss social justice issues and interrogate formal accessibility and AT policies and procedures, with the potential to subvert them in the future. Our lessons learned shows that using DIY-AT processes in university makerspaces can allow students to receive accommodations that the university might not give them, create AT that is a better representation of themselves, and have access to a range of expertise, including digital fabricators. Future work can explore how such processes can be part of a supportive ecosystem to enable creating designs led by students with disabilities to circumvent university restrictions and complement inflexible accommodation policies to support students with disabilities' success. We hope that our lessons learned inspire future research and action towards creating inclusive, accessible, antiracist, feminist makerspaces in university ecosystems as spaces of empowerment, self-efficacy, and solidarity for students with disabilities.

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