# *Simphony*: Enhancing Accessible Pattern Design Practices among Blind Weavers

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## ABSTRACT

The maker movement has garnered significant attention as democratizing design; yet, recent work has called attention to the challenges disabled people encounter in making. Although researchers have built systems to improve accessibility of maker technologies, limited studies have centered disabled people's engagement in traditional forms of making like fiber arts. We examine the practice of fabric pattern design among a community of blind weavers who create hand-woven products with sighted instructors. Grounded in seventeen interviews with blind weavers and sighted instructors, we built *Simphony*, an audio-tactile system that aims to support blind weavers in creating and perceiving patterns. Findings from eight design exploration sessions at the community studio reveal how blind weavers used Simphony to learn the process of pattern design and generate patterns with sighted instructors. We reflect on collaborative understanding of pattern design among blind and sighted individuals and discuss opportunities for integrating technological augmentations into traditional craftwork.

## CCS CONCEPTS

• **Human-centered computing → Empirical studies in accessibility**; **Empirical studies in interaction design**.

## KEYWORDS

Disability; design; making; accessibility; blind; weaving

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## 1 INTRODUCTION

Disability art, i.e., art created and performed by disabled people, is an integral part of the disability rights and justice movement [30, 77, 110, 116]. By offering varied representations of disability experience, disability art disrupts the ableist narrative that views disability as a deficit [130], exposes exclusionary social norms [10], and promotes a positive identity of disabled people that celebrates disabled life and disability community [47, 116]. Consider the following quote from one of our informants, Lisa,[1] a legally blind and nerve deaf musician, songwriter, and weaver who has been part of a community weaving studio for visually impaired adults for 9 years:

> *"Our music, our weaving, art is a part of our lives... In my case, as a visually impaired person—from spinning to knitting to crocheting to weaving... I wanna keep this art alive so that whether you go to a cultural center or civic center, you go through the Smithsonian, you see my legacy, you'll see it for plenty of years to come... Whether you knew my name or not... my name is in my work. This is who I was."*

The rich practices and innovative work produced by disabled artists have long been discussed within Disability Studies literature [130, 133, 135]; yet, disabled artists and makers like Lisa are rarely featured in the extensive scholarship on making and design. Recent HCI research has called attention to the ways elite status of design excludes and under-values labor of certain communities [11, 51, 89] including those of disabled people [95] and tends to view them as non-designers while positioning non-disabled people as designing for them [16, 17]. Relatedly, scholars have started studying why and how disabled people engage in making [15, 26, 64, 75, 120] and how their labor of making is valued [37]. Others have identified existing accessibility issues in makerspaces [95, 121] and maker technologies [27, 73, 74] and built new solutions to address these issues [106, 117]. Much of this prior work focuses on enabling opportunities for disabled people to perform making *independently* [27, 56, 75, 87, 95]. Recently, however, Disability Studies and accessibility scholars have started moving from independence to an *interdependence* perspective [14, 62, 96, 129, 132], highlighting the roles that both disabled people and their non-disabled allies and collaborators play in accessible making [37, 67, 68, 133]. Aligning with this rhetorical turn, our work examines the collaborative practice of fabric pattern design within a US-based community of blind weavers who create hand-woven products with sighted instructors.

To date, limited prior studies have investigated accessibility in traditional forms of making and fiber arts, although disabled people have a long history of involvement in these practices [23, 34, 50]. Moreover, fiber arts like weaving are often regarded as precursors of computing [49, 127] that foreground under-acknowledged stories of design [115]. The process of designing fabric patterns is algorithmic in nature in that weavers can produce numerous patterns by combining and repeating sequences in different orders. Pattern design also requires visualizing weaving sequences and fabric previews that portray various geometric shapes, e.g., diamonds, squares, or

*This work was done while Maitraye Das was at Northwestern University.

[1] All names are pseudonyms



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ovals. Thus, studying accessible pattern design can reveal new understandings of visual-spatial information processing [31, 83, 102] and algorithmic thinking among blind individuals. Furthermore, the limited prior work that did explore fiber arts practices among blind artists revealed that these artists value creating high-quality fabrics and unique designs that are not only visually appealing to sighted recipients but also aesthetically meaningful to themselves [20, 37, 56, 61]. Hence, to understand and enhance accessible making and fiber arts, it is important to examine the ways in which blind individuals engage in the design aspects of weaving—of which pattern drafting is a significant part—and develop new ways to make this process more accessible to blind weavers.

To this end, the present paper analyzes how blind weavers work with sighted instructors to design, plan, and execute the complex procedure of generating fabric patterns and introduces a new system to explore whether and how technology can augment their design workflow. Grounded in our formative interviews with fourteen blind weavers and three sighted instructors, we developed *Simphony*, an audio-tactile system that incorporates sonification techniques, spoken audio, and a tactile overlay to better support blind weavers in creating and perceiving fabric patterns. We report findings from eight design exploration sessions, detailing how blind weavers and sighted instructors used Simphony to generate new patterns together, what they learned from these activities, and how they valued and made sense of their creations.

Our work makes three primary contributions. First, we provide a deeper empirical understanding of how blind and sighted collaborators work together to anticipate the look and feel of the final woven product and conceptualize how a fabric comes into being from particular configurations of fibers and physical operations on the loom. Our findings complement prior research that explores the intersection of crafting and interaction design (e.g., [43, 49, 52, 115]), foregrounding the ways in which blind weavers engage in design work. Second, we introduce a variety of audio-tactile techniques to help blind weavers learn underlying mechanisms of weaving, revealing novel insights about collaborative understanding of pattern design. Third, by analyzing the case of pattern design, we discuss ways to integrate technological augmentations into traditional forms of craft and how blind artists can combine different art forms (e.g., music and weaving) to foster creative expression.

## 2 RELATED WORK

Our study extends the literature on digital augmentations in fiber arts, technologies developed to support accessible making and visual-spatial information processing as well as ongoing theorizing of interdependence in accessibility.

### 2.1 Digital Augmentations in Fiber Arts

Computer-aided tools have long been embraced by fiber artists, especially for designing fabric patterns (e.g., WeaveIt [7] and Fiberworks [2]). Simultaneously, researchers have been exploring new technological augmentations to fiber arts. For instance, Rosner and Ryokai [114] designed Spyn, a system that enabled knitters to embed digitally recorded messages into knitted fabrics. Albaugh et al. [8] investigated ways to create unconventional fabric patterns and assembled a handloom with 3D-printed parts that allowed various forms of flexible manipulation of patterns, such as by following a collaboratively edited draft pattern in real time [9]. Another example of a digital pattern fabrication tool is Loominary [124], a game where a fabric pattern emerges through players' moves as they input their choices using weaving materials. Devendorf and colleagues modified traditional weaving techniques (e.g., double weaving) [44] and developed smart textile designing tools that allow weavers to simultaneously draft weave structures and electronic circuitry [54] and create reusable, easy-to-unravel patterns [136]. Hofmann et al. [66, 69] built programming toolkits for generating knitting textures based on user-defined aesthetics. Others innovated non-traditional means for creating weave patterns, such as by using 3D-printed water-soluble drafts [42] or playing music on a digital device [137]. Although this prior work has developed a number of techniques to digitally augment fiber arts practices, these tools still require interacting with graphics-heavy interfaces that are not accessible to blind individuals.

### 2.2 Accessibility in Making Tools and Practices

Within HCI, a burgeoning body of work explores making practices among disabled people [26, 120]. Researchers found that engaging in making and fabrication helps disabled individuals develop a sense of autonomy, agency, and empowerment [75, 95] and challenge notions of normalcy [15, 64]. Others examined accessibility barriers associated with the design, adoption, and adaptation of maker technologies (e.g., 3D modeling software) [27, 73, 74] and physical makerspaces [95, 121]. Consequently, researchers developed ways to better support accessibility in digital fabrication and electronic circuitry tools and practices [106]. For instance, Siu et al. [117] built shapeCAD, an accessible 3D modeling workflow that helps blind people form a mental model of design objects through haptic feedback from a 2.5D shape display.

Closely related to our work are the studies that analyze fiber arts practices among disabled people. Gotfrid et al. [61] investigated accessibility challenges proficient disabled knitters face while creating knitting patterns. Giles et al. [56] conducted workshops with visually impaired people with little or no weaving experience, where participants created personalized art objects using e-textiles and beginner-friendly looms. Others incorporated semi-automated functionalities in a handloom [109] and built a system called Melodie that senses physical operation on loom components and emits musical cues to facilitate blind weavers' awareness of the loom state [20]. Collectively, this prior work focuses on improving accessibility in the physical operations of fiber arts that involve direct interaction with the loom. We complement this work by augmenting blind weavers' engagement in the *pattern design* process that happens *before* one starts weaving on a loom but has significant implications for how the end product takes shape.

### 2.3 Accessing and Understanding Visual-Spatial Information

Studying accessible pattern design can also deepen our understanding of how blind people process visual-spatial information more broadly, given that pattern design requires comprehending shapes, colors, and spatial positioning of different components within a fabric. Synthesized speech (e.g., screen reading), non-speech audio (e.g., earcons, auditory icons), sonification (i.e., mapping data values to sound parameters), and spatial audio are some of the most common auditory techniques that researchers have explored to support accessibility in visual-spatial tasks, such as understanding graphs and figures [1, 4, 53]. Compared to the linear and ephemeral nature of audio [102, 108], the spatiality and permanence of physical objects allow simultaneous exploration, for which tactile/haptic perception has long been a common method among blind people for processing spatial information [13, 28, 41]. Researchers have developed new tactile/haptic techniques such as using refreshable pin-matrix displays [21, 92, 108], 3D models built with fabrication tools [28], and force feedback mechanisms [53, 100].

Overall, sensory integration, i.e., enabling both touch and sound affordances better aid perception of visual-spatial content [31, 83]. For example, on touchscreen devices, blind users' understanding of spatial information and geometric shapes improved when proprioception from touch gestures were combined with screen reader announcements [102] or sonification [91]. To further facilitate blind people's understanding of spatial layout on touchscreen devices, researchers have built tactile [81, 88] and auditory overlays [80]. Others combined sonification with vibrotactile feedback on touchscreen devices [60] and physical icons on tabletop interfaces [94] to improve accessibility of graphical content. Despite this extensive research, the ways blind people process visual-spatial information while performing design work and collaboration with sighted people remains largely overlooked [83, 102] (for some notable exceptions, see [22, 35, 41]). We contribute to this literature by investigating how blind weavers utilize an audio-tactile system to design and perceive weave patterns together with sighted collaborators.

## 2.4 Interdependence in Ability-Diverse Collaboration

Accessibility research within HCI has predominantly centered around supporting disabled people in performing activities (e.g., navigation) independently [86]. Recently, however, Disability Studies scholars and activists have critiqued viewing independence as the ideal goal of accessibility [77] and instead shifted focus to the notion of interdependence [33, 62, 96, 111, 132], which "recognize[s] the value of depending on others and being depended upon" [131]. Drawing on this scholarship, Bennett et al. [14] positioned interdependence—rather than dependence or independence—as a way of challenging ability-based hierarchies in assistive technology design and illustrated how "people with heterogeneous abilities [...] pool their strengths to achieve shared access." The interdependence perspective underscores the "care work" [101] both disabled and non-disabled people perform to enable and sustain access and the mutual relationship forged in this process [18]. For instance, Goodwin [59] demonstrates how Chil, an aphasic man who can speak only three words, acts as a competent speaker by connecting his limited utterances and gestures to the elaborated talk and actions of others. Goodwin argues that Chil's ability to engage in meaningful conversation is "deeply embedded within the actions of others as they build lives together" [59]. Instead of minimizing or replacing human assistance altogether, researchers have started calling attention to the ways in which technology can amplify allyship and caregiving activities [67, 129], support relational maintenance [36, 119], and

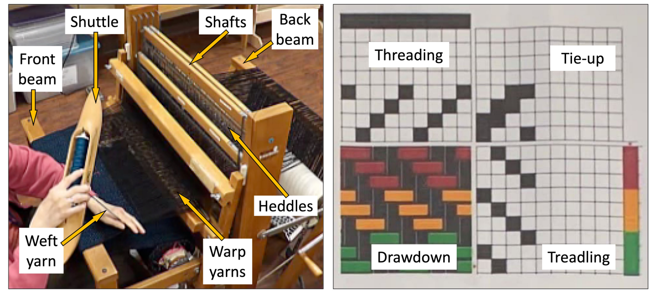


**Figure 1: Left: Basic components of a loom (e.g., warp, weft, shuttle, shafts, heddles, front and back beams) are marked. Right: Weaving draft of a twill pattern. See Section 3 for details about weaving drafts.**

play a meaningful role in the negotiation of ability and assistance [38, 126]. Similarly, although much of the prior work on accessible making has focused on facilitating independent making among disabled people [27, 56, 75, 87, 95], recent research has questioned the independence rhetoric, showing the roles of non-disabled collaborators in constructing access, such as clinicians ensuring the safety of fabricated prostheses [68] and family members and caregivers creating adaptations as a form of building their ally identity [37, 67]. We draw on and extend this body of research by centering the collaborative practices of blind and sighted weavers and enhancing how these ability-diverse groups generate patterns together.

# 3 BACKGROUND: WEAVING PROCESS AND DESIGNING A WEAVING DRAFT

Weaving involves interlacing two sets of yarns at right angles to form a fabric. The vertical yarns (called *warp*) are held stationary in tension between two beams at the front and back of the loom, while the horizontal yarn (called *weft*) is inserted over and under the warps (Figure 1, left). Between the two beams, warps pass through needle-like structures called *heddles*, each with an opening through which an individual warp yarn is passed. Heddles are suspended vertically from frames called *shafts*. Each shaft along with their heddles can be moved up/down to separate the warps into two planes, forming a vertical gap, i.e., *shed*. The movement of the shafts is controlled by pressing down *treadles* (i.e., pedals) by foot or pulling down *levers* by hand according to pre-defined sequences. The weft is then inserted through the shed using a carrier device called a *shuttle*. As the shuttle moves back and forth through the shed, it weaves an edge on each side of the fabric to prevent the fabric from unraveling. Each pass of the weft yarn is called a *pick*.

To ensure that the desired pattern appears on the fabric, a weaver needs to prepare a 2-dimensional set of instructions (called the *weaving draft*) [72] before starting to weave on a loom (Figure 1, right). The draft comprises three input panels: a *threading* sequence that decides which warp yarn will be connected to which shaft through heddles; a *tie-up* table that maps which shafts are tied to which treadles; and a *treadling* sequence that dictates the order in which treadles are pressed during weaving. These input panels determine the resultant fabric pattern, which is graphically represented in the *drawdown*, i.e., the 2D grid where each cell shows whether the weft yarn lies over or under the warp yarn at each intersection.

# 4 FORMATIVE STUDY: METHOD

To understand accessibility in pattern design, we conducted interviews with fourteen blind weavers and three sighted instructors with the approval from our fieldsite and the Institutional Review Board of Northwestern University.

## 4.1 Participants

Among our participants, twelve blind weavers were residents of a community weaving studio situated within an assisted living facility for adults with vision impairments and other chronic health conditions. Additionally, we interviewed two sighted instructors who taught weaving at the community studio. We learned from the interviews that the blind weavers at this studio did not directly participate in designing patterns; rather, they communicated their ideas and choices about colors and textures of yarns verbally to the instructors who then executed the planning, designing, and setup steps. As such, to better understand how blind weavers may directly engage in pattern generation, we invited (through snowball sampling) two expert blind weavers, Amy and Erin[2] and their sighted instructor Cora for interviews. Amy and Erin, who had over 25 and 7 years of weaving experience respectively, weaved at home on their personal looms and took part in every step of the design process, starting from planning a project, creating weaving drafts, and following the drafts to setup a loom. They were affiliated with a different fiber arts institute where they worked with other sighted and blind weavers during a week-long weaving workshop hosted every Summer. Table 1 details participants' self-reported disabilities, weaving knowledge, and relevant experience.

## 4.2 Procedure

We conducted semi-structured interviews between November 2020 and February 2021 using phone or Zoom—whichever participants preferred. Interviews started with collecting participants' verbal consent. While interviewing participants affiliated with the community studio, we asked them to walk us through how blind weavers came up with ideas for new projects or patterns, probing for what roles sighted instructors played in this process and how they supported weavers' involvement. During the sessions with expert blind weavers and their sighted instructor, we focused on understanding their design process in detail, especially how blind weavers created and read weaving drafts and how they adapted to any challenges they encountered while drafting patterns. We concluded by asking all participants to think openly about new ways of designing and understanding fabric patterns. After collecting participants' open-ended thoughts, we sought their opinions on exploring patterns on a paper-based tactile graphic, a braille display, or a digital app with musical sounds. Each interview lasted 60-90 minutes. Participants were compensated with US$30 each. All interviews were conducted one-on-one, except the one with Amy and Erin, who preferred to attend the session together over Zoom. We directly observed pattern design techniques for those who connected over video (i.e., Sara, Laura, and Erin). Interviews were either audio or video-recorded and later transcribed for analysis.

[2]Throughout this paper, we refer to Amy and Erin as 'expert' weavers to distinguish them from the blind weavers at the community studio.

## 4.3 Data Analysis

We analyzed data following the reflexive thematic analysis method [25]. We began by thoroughly reading and open-coding each transcript, taking an inductive approach. Next, we collated the codes into initial themes that captured phenomena such as understanding pattern formation, co-creating adaptations, and embedding meaning into fabrics. Through several iterations, we developed four final themes that highlighted salient aspects of blind weavers' pattern design process. Our analysis is shaped by our 3.5-year partnership with the assisted living facility, including the first author's eight-month-long in-person volunteer work at the weaving studio. Our immersion provided deeper insight into this community's values and ethos around promoting blind weavers' creativity through dynamic support and upholding their agency in securing assistance without overstepping to help. Nevertheless, we acknowledge that our position as sighted researchers inherently introduces power differentials in our relation with the community and shapes our analytic perspectives [25]. We discuss this further in Section 9.4.

# 5 FORMATIVE STUDY: FINDINGS

Our analysis revealed the ways in which blind weavers express themselves through pattern design, perceive patterns on woven fabrics, visualize patterns before weaving, and use tactile representations to facilitate their understanding of patterns.

## 5.1 Self-Expression through Pattern Design

Although blind weavers at the community studio did not directly take part in designing patterns, our interviews revealed that they deeply cared about creating aesthetically meaningful, high-quality products and decided upon various design parameters such as textures, colors, and acoustics of their woven pieces. To them, woven fabrics embodied a form of storytelling, where each yarn—through its unique texture and interrelationship with surrounding yarns—conveyed moments from the weaver's imagination or relics of their lived experiences. Lisa explained, *"As blind people, [we] want to tell a story using our senses, using our hands. And we want others to understand our world as well as theirs."* She described how her indigenous and African-American roots influenced her color choices: *"I want to do some African colors versus Indian colors...Brown, green, basically earth tones, the way we as American Indian tribes did."* As another poignant example, Helen made a memorial ribbon during the pandemic *"representing the people [who] lived here and passed on here (at the assisted living facility)...[with] blueish gray, then beige... and then red for the tip of the cane for the blind."* Developing a shared understanding of such entrenched values was critical for sighted instructors as well so that they could attune to the weavers' narratives while modifying design parameters of a project.

Interestingly, music was a key part of how many weavers expressed themselves through pattern design. Especially those who were proficient musicians felt that *"weaving and music go hand in hand."* Noah said, *"Whenever I play a note, it makes me think of different designs to weave with."* For Lisa, *"the softness of the instruments... the texture of the music"*—all evoked new imaginations about colors, textures, and patterns. In a communal project called "sound weaving" (Figure 2), these weavers attached to their woven pieces various objects that made sounds when touched or rubbed

**Table 1: Details of Participants. All names are pseudonyms. Phase of participation: Formative study (F), Design Exploration (DE). Draft design knowledge: Familiarity with threading, treadling, or drawdown.**

| Name (Phase) | Self-reported disability | Weaving experience | Draft design knowledge | Other relevant experience |
|---|---|---|---|---|
| Adam (F, DE) | Vision loss at the age of 7, 20/400 vision, glaucoma; Color-blind | 13 years† | Understands treadling & threading | Plays keyboard & concertina |
| Alice (F) | Visually impaired since birth, light perception, glaucoma | 2 years‡ | Data not collected | |
| Beth (F, DE) | Totally blind since birth, Retinopathy of Prematurity | 16 years† | None | Has 'perfect pitch', plays accordion & melodica |
| Eric (F) | Legally blind since birth | 2 years‡ | Data not collected | |
| Helen (F) | Totally blind since the age of 40, retina detachments and glaucoma | 8 years‡ | Data not collected | Some piano and music theory lessons |
| Jen (F, DE) | Totally blind since birth, Retrolental Fibroplasia | 3 years† | None | Plays piano & keyboard |
| Jim (F) | Legally blind, no vision in right eye, partial vision in left eye | 15 years‡ | Data not collected | Plays piano |
| Lisa (F, DE) | Legally blind, no vision at birth, gained some vision 4 years ago, Retrolental Fibroplasia; Nerve deaf, wears hearing aid | 9 years at the studio,† started learning as a child from grandma | Understands treadling & somewhat threading | Proficient musician, plays 67 instruments including harp, flute, & piano |
| Luke (DE) | Totally blind, vision loss since 2003, Diabetic Retinopathy & retinal detachments | 6 months† | None | Has programming knowledge; some piano lessons |
| Mark (DE) | Blind since birth, glaucoma & cataracts; wears cochlear implant | 5 years† | Understands treadling | Familiar with musical notes |
| Noah (F) | Visually impaired since birth, Retrolental Fibroplasia | 14 years‡ | Data not collected | Plays keyboard |
| Paul (F, DE) | Totally blind since birth | 4-5 years† | Understands treadling & somewhat threading | Plays piano; advanced user of computer & screen readers |
| Ruby (F) | Totally blind since birth | 4 years‡ | Data not collected | Plays piano |
| Tina (F, DE) | Can see up to 3 ft away, condition since birth, Optic Nerve Hypoplasia | 7 years† | None | Vocalist, plays tambourine; advanced user of computer & magnification tools |
| Laura (F) | Sighted | Taught at the studio for 12 years‡ | Design expert | Currently teaching at another assisted living facility; weaving since college life |
| Leah (DE) | Sighted | Teaching at the studio for 9 months† | Design expert | Weaving for 4 years† |
| Sara (F, DE) | Sighted | Teaching at the studio for 4 years† | Design expert | Took music lessons as a child; weaving for 13 years† |
| Amy* (F) | Totally blind since birth | Expert weaver & instructor; 25 years‡ | Design expert | Taught music and assistive tech at a school for the blind |
| Erin* (F) | Totally blind since 2 years old, Retinoblastoma | Expert weaver; 6-7 years‡ | Design expert | Computer specialist at a school for the blind |
| Cora* (F) | Sighted | Teaching blind weavers for 20 years‡ | Design expert | Weaving for 43 years‡ |

*Not affiliated with the community studio and works at a different fiber arts institute.
†Experience at the time of the design exploration study, i.e., May 2022.
‡Experience at the time of the formative study, i.e., November 2020-February 2021.

(e.g., bells, beads, aluminum foil, pop can tabs, cellophane, etc.) or are associated with music and personally meaningful to them, for instance, cassette tapes and guitar strings that the weavers owned and mp3 players with audio recordings of them *"doing the rhythm of the loom,"* i.e., performing weaving motions (Noah), playing instruments (Lisa), or imitating screen reader voices (Paul).

Thus, blind weavers at the community studio valued integrating their own narratives into the weaving process through textures, colors, and acoustics. However, inaccessible draft design tools coupled with inadequate resources and limited time for training (e.g., a small number of instructors and shared looms) made it challenging for these weavers to fully participate in pattern design. Still several

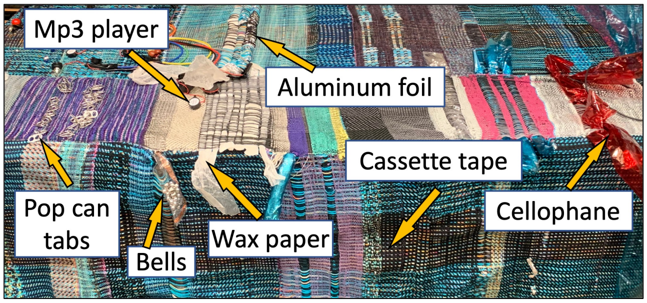


**Figure 2: A tapestry from the 'Sound weaving' project with an assortment of sound-making objects attached, e.g., cassette tape, bells, aluminum foil, wax paper, and mp3 players.**

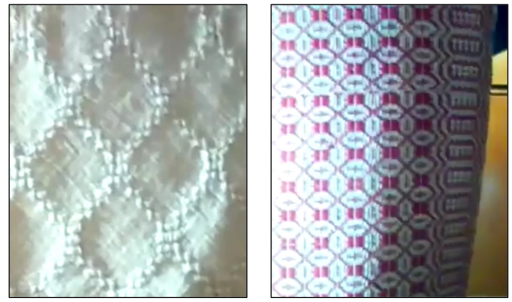

**Figure 3: Left: A pattern that Erin tactually perceives as *"ovals connected"* but her sighted collaborator perceived differently. Right: 'Overshot,' a composite pattern Erin created, consisting of different shapes in the corner and in the middle.**

weavers (Eric, Tina, Helen, Adam, and Beth) wanted *"to be shown what the pattern looks like in the instructors' book"* or to *"look at the computer program and try to copy what it looks like on the loom."* Paul, Ruby, and Tina even showed enthusiasm for listening to patterns where colors would be represented with music. Instructor Sara added, *"Giving them more to do with the [design] process would increase their involvement, appreciation and enjoyment of the whole activity."* These excerpts indicate the potential value of new design tools that can enrich blind weavers' creative expression through the fusion of music and weaving.

## 5.2 Iteratively Perceiving Patterns on Woven Fabrics

Although the blind weavers in our study were interested in taking a more active role in the design process, a key challenge involved perceiving fabric patterns. Echoing findings from previous work [20, 37], blind weavers shared that they *"can feel the zigzag of the designs"* (Tina) by tracing fabrics under their fingertips. To better detect patterns, expert blind weavers, Amy and Erin, inspected the fabric as it formed on the loom while weaving. Erin said, *"Diamonds, ovals, diagonals — everything stands out when it's under tension,"* whereas the shapes get *"harder to see"* (Amy) once the woven fabric is taken out of the loom because the lack of tension makes the yarns *"blend together."* Perceiving shapes by touch becomes even more difficult when yarns have fewer textures, patterns have intricate details, and when weavers have reduced dexterity or tactile perception ability due to other health conditions. In such cases, sighted instructors provided embodied guidance by drawing the pattern on blind weavers' arms or guiding their fingertips along the pattern while describing its visual-spatial properties. Amy explained: *"If something wasn't quite cemented in our head… If it's a more complex sample, she (sighted instructor) will take a fingertip and use it as you'd [use] a pencil. And she'll say, 'See how this diamond connects, see how this goes up and then down.'"*

Even when the textures in a fabric were tactually discernible, blind weavers sometimes found it difficult to gather a holistic picture of composite patterns that comprised smaller shapes spatially dispersed on the fabric (Figure 3, right). Since the emergent shapes connected with each other in multi-faceted ways, blind and sighted weavers constructed their own interpretations for the shapes, which did not always align (Figure 3, left). To develop a detailed understanding of composite patterns, Amy and Erin examined the fabric repeatedly as it formed on the loom thread-by-thread, incrementally unfolding the patterns. Blind weavers shared their excitement when experiencing a pattern for the first time this way. Erin exclaimed, *"Sometimes I'm just totally mystified and amazed! It's so wonderful to see a design I never even thought about pop up."* While there is a sense of joy and surprise in discovering new shapes serendipitously, having a precise understanding of the end product *before* starting to weave on a loom is important to ensure that the resultant pattern aligns with what the weaver intended to create in the first place, which we detail next.

## 5.3 Learning to Visualize Patterns Before Weaving

To design a weaving draft, weavers need to understand the underlying mechanisms of the loom and the weaving algorithm, specifically how the threading of warp yarns, tying of shafts and treadles, and the order of pressing treadles alter the resultant patterns. Sighted weavers can easily perceive this interrelationship on graphical draft designing applications, which display the output pattern immediately when changes are made to the input sequences. Since these applications are inaccessible, expert blind weavers *"visualized in [their] heads"* how a pattern would come out if they modified the threading, tie-up, and treadling in certain ways. Amy explained, *"I figure out—if I did this threading [sequence], it would make a diagonal to the right. If I did this, it would make a diagonal to the left. If I did this, it would make a square block..."* Thus, Amy and Erin engaged in a form of algorithmic thinking as they developed a mental imagery for resultant patterns based on numerical sequences. They referred to this process of formulating new patterns as *"drawing...a 3D picture"* (Erin) or solving *"a jigsaw puzzle–you just put [shapes] together and make them fit"* (Amy). Mastering this 'visualization' technique, however, required years of practice and honing their understanding of the weaving algorithm. These weavers also took inspiration from geometric *"design models"* such as the Fibonacci series and repeated smaller shapes in the order of 2, 3, 5, 8, 13, etc., to maintain aesthetics and integrity of their woven pieces. Building on established design concepts this way made the process of conceptualizing new patterns *"much less stressful for me,"* said Erin. They also frequently collaborated with each other to brainstorm unique design ideas. *"We love working together because we grasp concepts very similarly. And that really helps a lot,"* explained Amy.

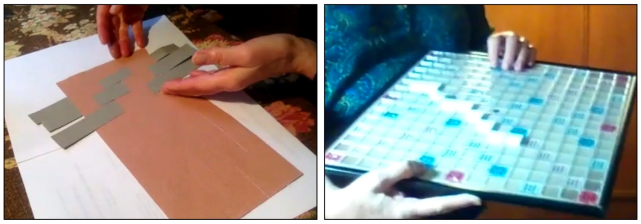

**Figure 4: Left: Laura (instructor) demonstrates a 'macro sample' for the twill pattern with interwoven paper strips. Right: Erin shows the scrabble board she used to draft and explore patterns. Pieces are arranged in a diagonal sequence.**

Still, it took them a long time to mentally calculate how a pattern would turn out, especially when they intended to design intricate, non-uniform patterns where the same shape did not repeat *"all the way across"* on the fabric (e.g., overshot in Figure 3, right). In such cases, they relied on trial and error, for example by weaving small samples on a loom while iteratively modifying sequences, to figure out what combination of threading, treadling, and tie-up would lead to their desired outcome. Alternatively, they wrote down numerical sequences in text documents using Microsoft Word and shared those documents with their sighted teacher Cora who then ran the sequences on a draft designing software to check for mistakes. Thus, inaccessible design tools put blind weavers at a disadvantage, where at best, they must use trial and error on the loom or rely on sighted collaborators to digitize patterns, or at worst, not participate in pattern designing at all.

## 5.4 Exploring Patterns through Tactile Representations

To address the complexities associated with conceptualizing fabric patterns, our participants adopted various techniques to facilitate blind weavers' tactile perception of patterns and formulation of weaving drafts. Some instructors thought that *"macro samples"* (Figure 4, left) made of rough yarns, ropes, or sandpapers could make it easier for blind weavers to *"identify when threads are going over versus under"* (Sara). Cora, however, noted this technique as *"exceedingly tedious to do"* for replicating complex patterns. Instead, she along with expert blind weavers Amy and Erin devised other adaptive solutions by repurposing everyday objects and building new bespoke tools. For instance, they reappropriated blind-friendly scrabble boards with raised gridlines and arranged scrabble pieces in different sequences to find the one that they liked the most (Figure 4, right). Erin also experimented with other strategies such as drawing raised lines on cellophane paper over rubber board or arranging square-head tacks on poster boards with small sticks of toothpicks glued on the tacks. These customized techniques still required significant cognitive effort for calculating drawdowns manually from numerical sequences. Amy and Erin, instead, wanted to use tools that would allow them to readily experiment with and compare different patterns as well as easily recreate existing drafts. Erin said, *"I don't want to have to create (calculate) everything I do. I like something my friend made—I just want to know how to recreate it."* They envisioned that preparing *"enlarged"* and *"raised"* copies of drawdowns with instructor Cora could potentially help them understand and build on pre-designed patterns.

## 5.5 Summary

Overall, our formative work illustrates three key insights for building accessible pattern drafting tools. First, blind weavers need accessible tools that can automatically generate output drawdowns from input threading, treadling, and tie-up sequences to allow for rapid exploration without having to expend undue cognitive effort and time for manually calculating patterns. Second, tangible materials that make individual warp-weft interlacements tactually more prominent and easily manipulable can help blind weavers perceive and alter intricate details of patterns that might otherwise be difficult to do on woven fabrics. Third, pattern design tools that combine multiple modalities and art forms seem promising for enhancing creative expression among blind weavers.

# 6 SYSTEM DESIGN AND DEVELOPMENT

Our formative study informed the design of SIMPhoNY (Sonified Interactive Musical Patterns for iNterlacement of Yarns), a draft designing tool to support blind weavers in creating, perceiving, and modifying fabric patterns through auditory and tactile feedback. Simphony consists of two components: (1) a web application primarily designed for tablet devices and (2) a wooden grid with blocks. We drew on prior research showing that audio-tactile representations better support blind people's spatial perception in complex tasks than either audio or tactile cues alone [31, 99, 108]. The design of Simphony was guided by an iterative process starting with formative interviews followed by a pilot session conducted with sighted instructors, Sara and Leah, at the community studio.

## 6.1 Digital Component: Simphony Application

Although weaving is fundamentally a tangible and embodied craft, we incorporated a digital application into the process to address the needs for rapid exploration and multimodal augmentation (Section 5.5). Moreover, much of pattern drafting nowadays is performed with the help of digital apps [2, 7, 54]. Similar to these drafting apps, the core functionality of Simphony is to auto-generate a drawdown (i.e., fabric preview) from input sequences such as threading, treadling, and tie-up (Figure 5). What sets Simphony apart from other drafting apps is that it incorporates a variety of text-to-speech and sonification techniques to make the pattern generation and exploration process more accessible to blind weavers. It supports standard tap gestures that blind people use on touchscreen devices, e.g., single tap for listening to an item and double tap for selecting/deselecting it. Simphony is implemented in Javascript using Web Audio API for audio effects and SVG.js and Bootstrap.css for visual renderings. Our code repository is publicly available.

*6.1.1 Sonification Techniques.* Simphony indicates the warp or weft yarns with a categorical audio parameter, timbre (i.e., tonal quality) of different musical instruments. Weavers can assign an instrument to warp or weft from eight available options chosen from diverse instrument families to allow for distinguishable variation in timbre. These are: struck string (piano), plucked string (guitar, harp), bowed string (cello), aerophone (church organ), brass (trombone), woodwind (saxophone), and percussion (vibraphone). We created short mp3 files for musical notes in an entire octave (C4 to C5) using each of these instruments from an online music sequencer

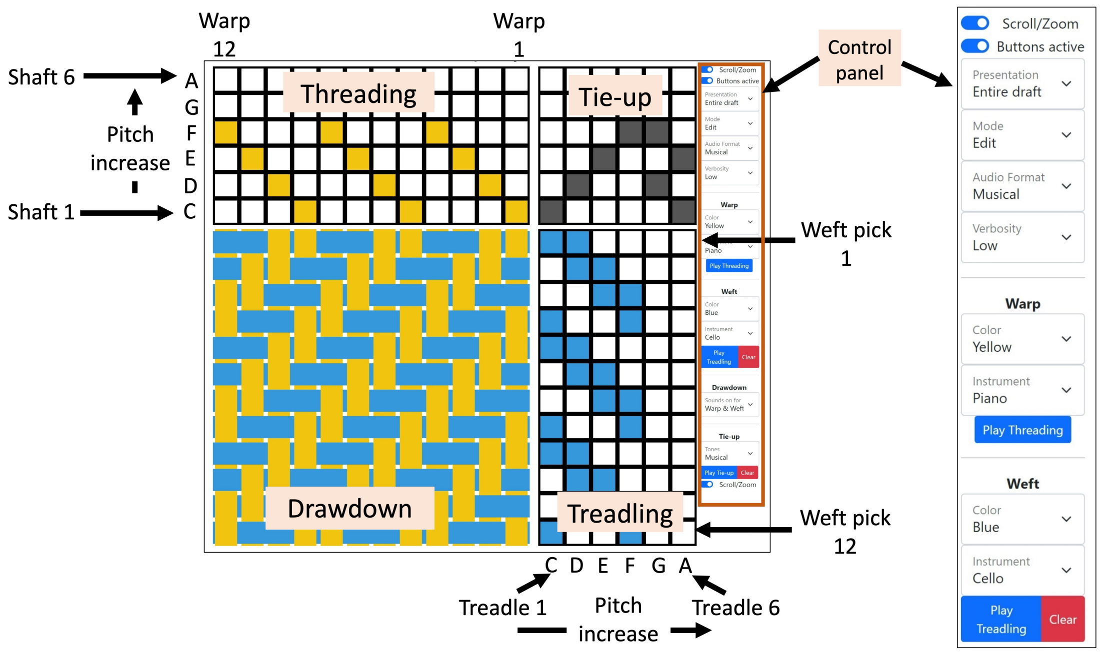


**Figure 5: A sample weaving draft for a 2x2 twill pattern on the Simphony app. The threading sequence is 1234 repeated three times. The treadling sequence is 12-23-34-41 repeated three times. On the right, part of the control panel is shown enlarged.**

[5]. Additionally, weavers can choose colors for warp and weft from eight options (red, green, blue, yellow, orange, pink, purple, and black) that are frequently used at the community studio.

Since pitch variation is widely used to indicate changes in successive data values [53, 83], Simphony maps numerical sequences onto musical notes with varying pitch. Each row in the threading sequence (i.e., shaft) and each column in the treadling sequence (i.e., treadle) is represented by a distinct musical note, with higher indexed shafts/treadles corresponding to a higher pitched note. In the tie-up table, columns and rows stand for treadles and shafts respectively. Here, each row (shaft) is denoted by a distinct note played on a piano, with the pitch increasing for higher indices. Another audio parameter (volume) changes across columns, where the leftmost column (treadle 1) has the highest value and the rightmost column has the lowest. In case of the drawdown, tapping any cell plays the C4 note in the instrument assigned for the warp or the weft, depending on which yarn is visible on the cell.

Besides identifying individual shafts or treadles in a sequence, weavers can listen to the entire threading, treadling, or tie-up sequences. For the threading sequence, corresponding notes for activated cells are played by column from right to left, following a common convention for reading weaving drafts. In the draft on Figure 5, the warp (yellow) and the weft (blue) are denoted by piano and cello respectively. Simphony maps notes C4, D4, E4, F4, G4, and A4 played on a piano onto shafts 1-6 and the same notes played on a cello onto treadles 1-6. Thus, the musical representation for the threading sequence 1234-1234-1234 is CDEF-CDEF-CDEF, played on a piano. Unlike threading, multiple cells can be selected in a row (i.e., weft pick) of a treadling sequence, which required us to modify the presentation technique for the entire sequence. In this case, notes for activated cells in a treadling sequence are played by row starting from top to bottom. Within each row, notes are played for the cells from left to right and a short blip earcon is inserted as a separator between adjacent rows. Playing the entire tie-up follows a similar process [107].

*6.1.2 Spoken Announcements and Customizable Modes.* Based on feedback from the pilot session, we incorporated a 'Verbal' (i.e., spoken audio) mode, in which single tapping a cell in a threading, treadling, or tie-up sequence reads out the shaft/treadle number of that particular cell and single tapping a cell in the drawdown reads out '`Warp`' or '`Weft`' to indicate which yarn is visible. In both 'Verbal' and 'Musical' (i.e., sonified) modes, selection/deselection of a cell by double tapping is confirmed with a spoken alert: '`Shaft 1 Warp 1 on/off`' (for threading), '`Treadle 1 Weft 1 on/off`' (for treadling), or '`Shaft 1 Treadle 1 tied-up/not tied-up`' (for tie-up). There is a 'Verbosity' control that allows weavers to shorten this spoken alert to '`on/off`' or '`tied-up/not tied-up`.' Simphony also enables a 'Read' mode where the cells become read-only i.e., not editable, and only the activated cells play sound or spoken audio on being tapped while the empty cells remain silent. Spoken phrases were pre-generated using macOS text-to-speech feature with the voice profile Samantha (US accent).

Typically, a weaving draft shows all four panels (threading, treadling, tie-up, and drawdown) arranged together. However, considering the needs of visually impaired weavers, Simphony allows people to separately interact with enlarged versions of individual panels. For the sake of simplicity, it currently supports creating patterns for a loom with 6 shafts and 6 treadles, with sequences up to 12 warp yarns or 12 weft picks long, resulting in a 12x12 drawdown. For our design exploration sessions, Simphony was deployed on a Windows Surface Pro 8 tablet.

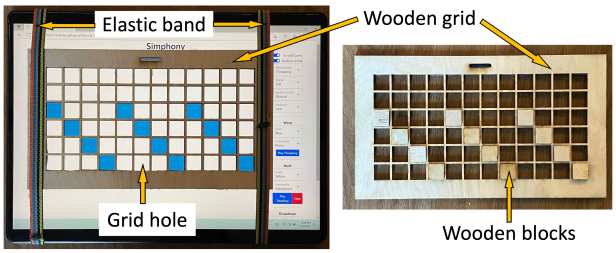


**Figure 6: Left: A wooden grid is secured on top of the tablet showing the enlarged threading sequence of a twill pattern on Simphony. Right: The same threading sequence is created with wooden blocks on a standalone grid.**

## 6.2 Tangible Component: Wooden Grid with Blocks

We brainstormed with interview participants about various alternatives for an easily perceivable and manipulable tactile representation of patterns (Section 5.5). Using refreshable tactile graphics displays [3] or 3D printers did not appear to be a sustainable solution for the community studio due to these devices' prohibitive cost and the requirement of expert knowledge about specialized software (e.g., AutoCAD) and hardware [90]. We deliberated over reappropriating a braille display to show patterns with raised pins. However, the limited real-estate on the display (only 4 rows) makes it challenging to perceive larger shapes [22]. Moreover, perceiving shapes on a braille display could be *"a mind bend"* (Sara) for braille readers because they would need to stop reading the raised pins as braille characters. Additionally, for weavers with reduced tactile sensation, the raised or lowered dots on the braille display or tactile graphics display could be *"too small"* to feel and thus, it would have been *"very, very, very tricky"* (Helen) to discern interlacement structures. Tactile image maker devices [6] could also be used to generate swelled-up versions of patterns that are manually drawn or printed onto heat-sensitive capsule papers, but weavers would still need a separate interface which would allow them to rapidly manipulate input sequences before deciding on desired patterns.

Given these constraints, we chose to develop a low-tech tactile solution involving a wooden grid that can be secured on the tablet with two elastic bands (and removed as needed). The design of the grid is informed by tactile overlays and 3D-printed keyguards that have been found useful for improving accessibility of touchscreen devices for people with motor or vision impairments [81, 82, 88]. The grid is laser-cut with holes through which a weaver can tap on the tablet and listen to auditory feedback. The 12x6 grid aligns with the enlarged views of the threading or treadling sequences on the Simphony app (Figure 6). Since the dimensions of individual cells in any sequence are the same, weavers can adjust the grid to align fully with the threading, treadling, or tie-up, and partially with the drawdown (the entire drawdown can be explored part-by-part). To reduce chances of the grid sliding over the glass screen [81], a thin Nitrile layer was attached underneath the grid that increased friction between the two surfaces. In addition, we made wooden blocks (13mm x 13mm) that can be placed into the holes of the grid. The height of the blocks (6mm) is double the height of the grid walls (3mm); thus creating a raised surface when the blocks are put inside the grid holes. Besides working as a tactile overlay for the tablet app, the grid (with wooden blocks) can also be used as a standalone tangible display. We made two identical grids to be used simultaneously in both ways. After completing our study, we left the grid and blocks at the community studio so that weavers and instructors can continue using those for pattern design [65].

# 7 DESIGN EXPLORATION: METHOD

With approval from our fieldsite and the Institutional Review Board of Northwestern University, we conducted eight design exploration sessions at the community weaving studio in May 2022.

## 7.1 Participants

Eight visually-impaired weavers and two sighted instructors took part in the design exploration sessions. Instructor Sara attended the sessions with Luke, Lisa, Tina, and Adam; instructor Leah participated with Jen and Paul; and both instructors joined the sessions with Beth and Mark. This arrangement follows the typical work configuration at the studio where one or both instructors teach and assist weavers at a time. Recruitment and scheduling were done consulting with the instructors. All participants except Luke, Mark, and instructor Leah were involved in our formative interviews. Each session lasted 90-100 minutes. Once all the sessions were over, we conducted a 75-minute debrief interview with the instructors. Participants were compensated with US$60 for each session they joined. Table 1 shows the details of participants.

## 7.2 Procedure

We adopted a naturalistic workflow for the design exploration sessions and asked participants to fluidly adapt their course of actions as they deemed fit. The main activity across all sessions involved creating and exploring the threading, treadling, and drawdown for '2x2 twill,' a basic pattern that weavers create when they start learning. Our goal was not to measure blind weavers' performance in designing patterns independently. Instead, taking an interdependence perspective [14, 96, 129], we aimed to uncover how blind weavers interact with sighted instructors and various materials in their workspace to learn, create, and make sense of fabric patterns and how technological augmentations reshape their collaborative work process and artistic expression.

Each session started with obtaining participants' verbal consent and collecting information about their familiarity with pattern design. No weavers were familiar with the term 'drawdown' although some had an understanding of treadling and/or threading. The instructors guided the weavers to understand these concepts by interacting with a loom positioned beside them (Figure 7, left). Instructors then explained different components and functionalities of Simphony. Per instructors' suggestion, weavers first created threading and treadling sequences of the twill pattern by arranging blocks in the wooden grid using it as a standalone tangible display. Next, they replicated these sequences on the digital application and listened to their auditory representations. Following this, weavers explored the drawdown for the twill pattern on the tablet, using the grid and blocks, and on a 'macro sample' instructors had created with felt strips prior to our sessions. Weavers also experienced the twill pattern on an actual fabric that we had selected from the inventory of the studio consulting with the instructors. However, weavers thought that the weft and warp and their interlacements


**Figure 7: Left: Lisa explores the pattern on an actual fabric. The workspace shows a tablet with the Simphony app, two wooden grids, blocks, fabrics, and felt samples placed on a table. A loom is positioned between Lisa and Sara (instructor). Right: Weaving drafts created by Tina (diamond pattern) and Luke (scale pattern) on Simphony.**

were *"hard to separate"* (Mark) on the felt macro sample and the actual fabric. Hence, we primarily report findings related to weavers' interaction with the Simphony system in Section 8.

All sessions were video-recorded with two cameras. Throughout the sessions, we asked questions to the weavers in-the-moment to capture how they made sense of the new concepts, perceived the sequences they created, and conceptualized repetitive over-under arrangement of yarns and emergent shapes on the drawdowns. We concluded with debriefing questions regarding weavers' reactions to the auditory and tactile features, probing them to reflect on whether and how they might use Simphony for performing design activities at the studio, and ideas for further improvement.

## 7.3 Data Analysis

We followed the reflexive thematic analysis method [25], which provided us a flexible way to holistically analyze various types of data [24] including interview transcripts, video recordings, and photographs captured. We started by reading and open-coding transcripts of verbal conversations while simultaneously reviewing the video recordings. Informed by Kafer's [79] political/relational model of disability and other Disability Studies literature [62, 77, 101, 131], our analysis views disability and access as enacted through "particular sociomaterial arrangement of relations" [97] and interdependence between bodies, technologies, and the environment [14, 33, 96, 132]. Further, we understand interaction as multimodal, embodied, and situated [58, 71, 122, 123] and attend to how blind weavers developed shared meaning with sighted instructors and the system. While analyzing the video data [19], we looked for salient interactions that captured, for example, blind weavers performing sequential exploration on Simphony, sighted instructors providing hand-over-hand guidance, and so on. Although we took short notes on all episodes of such interactions, we produced detailed memos for selected unique vignettes. For this, Das repeatedly watched certain video segments, writing down turns of events, timestamps, verbal and non-verbal interactions (e.g., hand postures, gestures), and auditory feedback from Simphony. Through iterative comparison of codes and data and regular discussion as a group, we constructed three overarching themes that described how blind weavers and sighted instructors used Simphony for generating patterns together.

# 8 DESIGN EXPLORATION: FINDINGS

Below we detail how participants created and explored patterns with Simphony, the potential for the system to affect weaving instruction and learning, and reflections on what it means to participate more fully in pattern design.

## 8.1 Creating and Exploring Patterns with Simphony

For all eight weavers, our sessions were their very first attempt at learning pattern design and interacting directly with a draft designing tool. Since these sessions were introductory, our participants' primary goal was to successfully put down input sequences that would result in unique fabric patterns. Besides the twill pattern recommended by the instructors, several weavers laid out the draft for an additional pattern they decided on their own. Luke, Paul, and Tina opted for 'scale,' 'flower,' and 'diamond' patterns, respectively (Figure 7, right), while Mark and Adam chose specific threading or treadling sequences (e.g., 1234321) instead of the outcome pattern. Below we describe how blind weavers used Simphony to create, explore, and understand these patterns.

### 8.1.1 Maintaining Awareness and Navigation.

Generating weaving drafts requires weavers to develop moment-to-moment awareness of the design interface, their actions within it, and how these actions alter the system state. In graphical draft designing applications, sighted people can easily manipulate the selection of individual cells in the threading, treadling, or tie-up sequences and immediately observe how their actions modify those sequences and the resulting drawdown. Our blind participants engaged in a similar process where they learned to attend to the auditory cues from Simphony to identify their current position in a sequence and detect how their actions changed the state of individual cells (on/off) as well as the entire sequence. When navigating from cell to cell on the digital *"flat"* interface, blind weavers made use of the additional tactile cues they received from the wooden grid placed over the tablet. Luke explained, *"Because of the tactile [feedback]... I know that I have moved over one [cell] because I've run into one of the [grid] walls. So, it makes interacting with the software, I'd say, possible at this point."* Thus, the grid worked as a marker that helped weavers find their way around the complex design interface.

Blind weavers also used auditory and tactile feedback to perform a synchronized routine of bimanual operation [13, 85, 92, 99] for laying out weaving sequences. They located the next target cell with reference to their current position in a sequence and marked it using one hand as *"a guide,"* while selecting/deselecting the cell with the other hand. When doing so, the audio cues helped weavers interpret whether they were on the right track or not. Consider the following vignette (Figure 8, left):

*(Beth tapped shaft 6 of a column in her threading sequence)*
***Simphony**: 6.*
***Beth**: Oh my god! We don't want that.*
*(Started sliding finger down the column while tapping each cell.)*
***Simphony**: 5. 4.*
***Beth**: Okay okay. (She was looking for shaft 4 and found it.)*

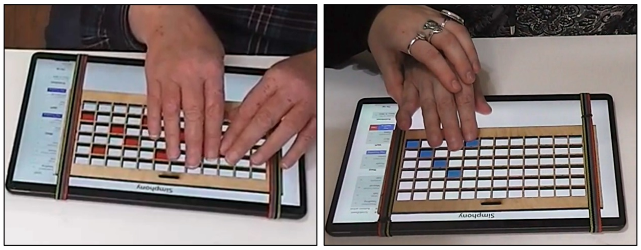

**Figure 8: Left: Beth locates the next target cell in her threading sequence, marks it with one finger, and uses another finger to select it. Right: Instructor Leah provides hand-over-hand support to Jen for locating a new starting point on her treadling sequence.**

As the above excerpt illustrates, blind weavers decoded the audio cues to figure out if they had accidentally pressed a wrong cell and how they should operate next to get their desired sequence. Still sometimes they struggled with detecting the last cell they activated in a sequence or locating the next target cell, especially if they took their hand off the grid and *"lost their place"* (Sara) at any instance. In such cases, sighted instructors provided hand-over-hand guidance to help weavers *"know where to start"* (Leah) and orient themselves accordingly (Figure 8, right). Thus, blind weavers leveraged the complementary interplay of audio cues from the app, tactile feedback from the wooden grid, and embodied guidance from sighted instructors to maintain awareness of and navigate within the system.

*8.1.2 Customizing Auditory Feedback.* How blind weavers reacted to and customized auditory cues from Simphony depended on their personal preferences, skills, and contexts of use. Several weavers found spoken audio easier, straightforward, and *"more accurate to read"* (Adam) than sonified representations. That is, translating sonified data to corresponding shaft/treadle numbers might have incurred additional cognitive burden for these weavers [39, 40, 53], given their lack of familiarity with the design concepts. Although several weavers preferred spoken audio (Tina, Luke) or wooden blocks (Jen, Adam) to formulate weaving sequences, all of them wanted to switch to the sonified representation *"to hear how it would sound in music."*

Disability experiences also shaped the way weavers made sense of audio cues. Mark who was hard-of-hearing preferred spoken audio, *"because my ears don't detect each note clearly enough… My [cochlear] implants weren't designed for music."* Unlike Mark, Lisa who also had hearing impairments preferred musical feedback to spoken audio. She explained, *"I miss words so easily because I'm nerve deaf… Computerized speech is very hard for me, even though I'm wearing hearing aids."* Instead, Lisa attended to the vibration caused by different instruments flowing through different parts of her body. She explained, *"The warp...instrument (saxophone) vibration came up right into my face. When I was hitting the weft, which was vibraphone, I could feel it right here (pointing at her right hand)—it's like ZZZ-kt ZZZ-kt!"* At the beginning of her session, Lisa tried out a number of instruments to determine the ones that would provide her with an optimal embodied sensation. Her proficiency in playing instruments also made her *"resonate better with music."* As these examples demonstrate, how weavers comprehended and customized auditory cues was influenced by their disability experiences as well as other aspects of their knowing and being.

**Figure 9: Left: Luke explores the drawdown for the 'scale' pattern on the Simphony app. Right: Jen runs both hands simultaneously over the wooden blocks arranged in the grid according to the drawdown for the 'diamond' pattern.**

*8.1.3 Perceiving Repetition and Order in Patterns.* Weaving sequences (and the resultant drawdowns) are formed by repetition of smaller units of interlacement structure in various orders and combinations (e.g., a diagonal repeated over and over again with upward or downward slope). Understanding and manipulating the order in which shafts (and associated warp yarns) get raised or lowered, how many adjacent warp yarns alternate with and float over the weft, and what shape emerges and repeats in the fabric is critical to designing a draft. All these elements determine the appearance, stability, and 'feel' of a fabric. As such, one of our central goals was to uncover how blind weavers perceived the weaving drafts they laid out on Simphony and made sense of the repetition, order, and shapes appearing in these draft patterns. Although our sessions were the first time blind weavers at the community studio tried to identify the lower-level details of patterns, weavers could determine the repetition and order of numbers (or musical notes) in threading and treadling sequences immediately after they listened to a sequence in full. For instance, upon listening to the musical representation of her threading sequence (1234-1234), Lisa commented, *"The progression of the sound… is repeating. It doesn't go backwards. It stays in the same forward motion. CDEF-CDEF is what that is. And there's a rhythm to that."* This rhythm in the sonified representation helped Lisa visualize the repetitive sequence.

A more complex part of the design process involves identifying whether the warp is more prominent than the weft (or vice versa) on the drawdown—a property that alters the appearance, density, and 'drape' i.e., fluidity of a fabric. Consider an example where Luke reasons through this aspect of pattern design. While reviewing the 'scale' pattern he recreated on Simphony—the same pattern he was weaving on an actual fabric at that time—Luke identified that the drawdown exposed more wefts than warps in a particular region (Figure 9, left). Before using Simphony, he was under the impression that *"the cloth [showed] mostly the warp with a line of weft."* Later Luke realized his initial misunderstanding by paying attention to how many times the warp and weft instruments were repeated. He explained, *"It was basically a process of disconfirming my belief. I knew that if what I thought was true, then it would be majority vibraphone (warp instrument). As I went through, I'm just like, it seems to be much more guitar (weft instrument)."* Thus, by experimenting with Simphony, Luke was able to comprehend the repetition of weft and warp yarns in the drawdown and better conceptualize how his final woven product would take shape.

*8.1.4 Understanding Composite Patterns and Shapes.* The resulting output from a specific combination of input sequences on a draft is a unique shape or pattern on the drawdown. To comprehend shapes emerging on a drawdown, blind weavers sequentially explored cells in a vertical, horizontal, or diagonal direction and then reconstructed shapes mentally from the audio cues they heard. For simple shapes like diagonal lines on a twill pattern, this process was relatively straightforward. However, many patterns result in complex and composite shapes that do not follow a straightforward, linear contour (e.g., diamond, oval) and are difficult to conceptualize through sequentially aggregating audio cues only. To supplement weavers' understanding from the audio cues, sighted instructors sometimes recreated the drawdowns with wooden blocks. Blind weavers felt that this presentation made the pattern *"more tangible, easier to keep track of... [and] feel the parallel pattern of warps and wefts with both hands"* (Mark). The tactile sensation weavers received from the blocks by exploring with both hands—although still sequentially—provided enhanced affordances for developing a mental imagery of the shape [29, 112]. Interestingly, instructor Leah observed, *"how the weavers oriented [themselves] when they're tracing"* a pattern and which direction they moved their fingers during exploration impacted their interpretation of emerging shapes [85, 99]. For instance, when exploring the diamond pattern created with the wooden blocks, Jen described the shape as a cross (✝), upon repeatedly moving both hands from left to right and bottom to top (Figure 9, right). Unlike such sequential exploration techniques adopted by the blind weavers, low-vision weavers (Adam, Tina) used their partial vision to scan the drawdown as a whole. This indicates the fundamental differences in the ways blind, low-vision, and sighted weavers tracked patterns.

One challenge we observed across the sessions was that the enlarged nature of the grid and blocks affected how weavers understood shapes. Instructor Sara explained, *"When you're trying to build a shape with a bunch of squares, it's gonna feel pixelated."* Perceiving a shape that consists of smaller shapes (i.e., squared blocks) is fundamentally different from perceiving a geometric shape that follows a continuous contour and is presented through, for example, a raised-line drawing [84]. Thus, identifying a shape on a weaving draft is not only about piecing together perceived information but also about filling out the gaps and mismatches in the perceived information. That's why, for blind weavers, these emergent shapes were mostly open to individual interpretations, which sometimes did not match how sighted people visually perceived those, as also surfaced in our formative interviews (Section 5.2). In such cases, sighted instructors fluidly adapted their vocabulary and engaged in dialogic interaction [57] with blind weavers where both collaborators articulated how they understood a shape, considered each other's perspectives, and made a bridge between individual interpretations of a shape and how that shape is traditionally described in weaving terms. During the debrief, Sara explained this process of shared meaning-making through reciprocal dialogues: *"When people were describing it (a diagonal pattern) as a staircase or steps, it's not wrong. And I tried to help them understand that they were correct in what they were observing... But it is something else too. It's just, how are we looking at this? And what is this on different scales?"* That is, the scale and resolution (e.g., dimensions of a unit) also impacted blind weavers' perception of shapes in a pattern [103].

In summary, blind weavers used audio-tactile cues of Simphony to perceive interlacement structures and come up with unique interpretations of resulting shapes. Furthermore, they interacted with sighted instructors to recognize how their tactual interpretation of a pattern on the drawdown could differ from instructors' visual description (or even their own perception on a real fabric), and yet, be part of a shared meaning that they build together.

## 8.2 Transforming Learning and Instruction Processes

Our analysis revealed that Simphony provided blind weavers with new modalities and vocabulary to learn, reconfirm, and retain complex weaving concepts. Further, the diverse interactions afforded by the digital and tangible components enabled instructors to customize their training strategies to suit weavers' individual learning styles, interests, and aptitudes.

*8.2.1 Learning and Solidifying Weaving Concepts.* Since blind weavers at the studio did not directly engage in the design phase, many of them lacked precise knowledge about how their *"physical actions of weaving"* translated into patterned fabrics. By creating a *"digital woven fabric"* first-hand on the *"computerized loom"* (as Lisa called Simphony), weavers felt that they were able to *"appreciate what's actually happening"* when they performed weaving motions on a physical loom. Luke detailed how interacting with Simphony helped him decipher the underlying mechanisms of weaving.

> *"I understand a little bit more about how the loom works from the demo... because this [application] is going to tell me which of those heddles is going up or down. And then on there (pointing at the loom), that's attached to the treadles that I'm manipulating directly. So, exploring it (Simphony) has made it easier to visualize both fractions going towards each other—the mechanics and the design... And the loom makes it all happen."*

Luke's comment reveals several important insights. First, by manipulating the selection or deselection of cells representing shafts in a sequence on the digital app, Luke gained a new knowledge that some heddles (and associated warp yarns) get raised when corresponding shafts are lifted. Second, by juxtaposing this new understanding with his prior knowledge from operating treadles on physical looms, he was able to comprehend the connection between treadling and threading—that these two components are interlinked, physically and conceptually. Thus, by making use of Simphony as a *"visualization tool,"* Luke was able to piece together what he experienced physically on the loom earlier in the session (see Section 7.2), what he learned by manipulating symbolic representations on the app, and his prior knowledge to form a coherent understanding of the principal mechanisms of weaving.

Some weavers were able to apply the new concepts they learned during the design exploration sessions in their subsequent weaving activities. During the debrief interview, instructors recalled an instance where Mark was encountering a mechanical issue with the treadles on his loom and he referenced the concepts he learned from his interaction with Simphony to discuss and comprehend what caused the error. Thus, instructors felt that Simphony provided themselves and blind weavers *"more language"* to talk about the inner workings of a loom and *"describe what's happening with more than just words"* (Sara). Leah added, *"Without this I wouldn't be able to verbally explain [the design process]… It would be very difficult."* These excerpts highlight the potential of Simphony as a scaffolding tool that sighted instructors and blind weavers can utilize for teaching and learning foundations of weaving.

*8.2.2 Facilitating Personalized Learning.* Our analysis revealed that Simphony, with its customizable auditory and tactile features, enabled new opportunities for personalized learning and teaching practices among blind weavers and sighted instructors. Instructor Sara commented, *"Each of them is thinking about it (pattern) from a different perspective. And this tool was very helpful in uncovering those different perspectives."* The session with Lisa presented a compelling example of this phenomenon. In her regular work, Lisa often *"drew a blank"* while memorizing treadling sequences in a numerical format, leading to errors in her weaving. In contrast, the material arrangement of wooden blocks helped Lisa better understand the sequence, where she could physically feel and manipulate the raised shape and what each individual treadle was doing [76]. She explained, *"The numbers– sometimes I get confused. But if this [grid] was in front of me… that would stay [in] my mind as a visual, a mental loom… That's why it clicked so well with the treadling sequence... And I've been weaving for years but I've never seen it hit me right here… This made everything come alive."* Besides the wooden blocks, participants thought that musical representations could be *"an incredible aid"* for weavers like Lisa who found it difficult to memorize abstract numbers and *"instead think in a tune."*

Sighted instructors attended to how individual weavers reacted to various audio-tactile cues and attuned their teaching strategies accordingly. Sara explained, *"How I was describing threading to Adam or Beth was totally different from how I would describe it to, say, Paul... To him (Paul), it would mean nothing if I said CDEF (musical notes), but to Beth (who had 'perfect pitch' recognition ability), that's exactly what she heard and it made sense to her."* Instructors also considered weavers' comfort level with technologies while deciding if the tablet app *"would be a good place for them to start or not."* These excerpts indicate that Simphony helped instructors and weavers elicit common ground [32, 55], i.e., mutual knowledge of what their collaborators understood so that they could leverage this knowledge to establish shared meaning in conversation and orchestrate learning and design activities accordingly.

## 8.3 Valuing Enhanced Engagement in Pattern Design

To our participants, Simphony's value moved beyond its effectiveness in supporting the process of generating and perceiving patterns and enabling new learning opportunities. Blind weavers also appreciated how they could leverage Simphony to take a more active role in the design phase alongside sighted instructors and find new avenues for artistic expression by combining music and weaving.

On the whole, blind weavers enjoyed creating fabric patterns using Simphony, calling it as *"a fun way to learn new things"* (Mark). The musical representation of weaving sequences, with timbre of different instruments and notes arranged in repetitive progression, engendered rich emotions among weavers. Listening to her threading sequence played on an organ, Jen felt *"like something exciting is going to happen,"* whereas with the version played on a guitar, she did not feel *"quite as much excitement."* Paul noted his treadling sequence (343-212-343-212) as *"relaxing,"* while Tina thought that her treadling sequence (12-23-34-41) *"sounds like a happy, skipping song."* Thus, blind weavers ascribed unique meanings to the weaving sequences—be it either memory of a song or the feeling that the song engendered—similar to the way they articulated personal narratives through their woven tapestries (Section 5.1). Several weavers commented that they would like to integrate Simphony *"as a supplementary tool"* at the beginning of their regular workflow to explore different patterns before committing to any particular design. Luke said, *"This whole experience has made me much more hopeful that I can actually come up with my own stuff, in terms of patterns or unique final product, whereas it was just kind of a mystery. I didn't know what was really possible."*

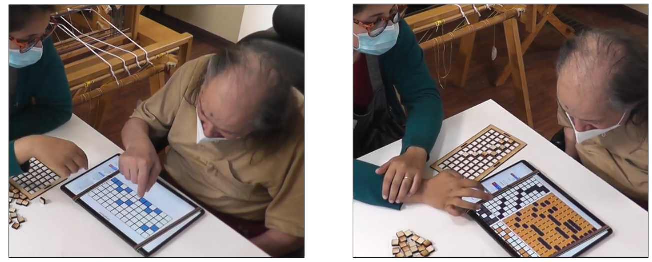

**Figure 10: Left: Adam creates a threading sequence inspired by the melody of 'Happy birthday to you.' Right: Instructor Sara demonstrates Adam a drawdown that could possibly result from a threading sequence he created from the melody of 'Mary had a little lamb.'**

The sonified presentation of weaving sequences also created opportunities for weavers to develop a unique fusion of two different art forms that they participated in and evoked new artistic inspiration. As a telling example, Adam generated threading sequences inspired from the melodies of 'Happy birthday to you' and 'Mary had a little lamb' (Figure 10). To him, deciphering how a melody would come out in the form of a fabric pattern seemed like a *"detective work"* for solving *"a mystery."* Like Adam, Lisa was enthusiastic about translating a song she composed herself into a fabric pattern. These weavers (and also Luke) ideated advanced ways of rendering a song as a pattern – features that were not yet available on Simphony. They came up with the idea of representing multiple treadles activated in a single weft pick on the treadling sequence with musical chords, i.e., multiple notes played simultaneously. Similarly, Lisa brainstormed with instructor Sara about denoting the duration of notes or chords in a song by having the weft *"float over"* equivalent number of adjacent warp yarns. Weavers also envisioned Simphony to be an embodiment of performative art, through which they could present their work before an audience. Jen wanted to organize public exhibitions to encourage other disabled residents to get involved in pattern design. Lisa similarly planned for a synchronized orchestral performance, saying: *"It could be done [in] a musical where you are weaving and...the song is turned into cloth."*

In this way, for blind weavers at the studio, Simphony opened up a pathway to foster their creative potentials by bridging the arts of music and weaving. Weavers' desire to get more involved in pattern design, however, was not positioned from the perspective of achieving 'independence.' Instead, they thought that designing on Simphony could lead to deeper collaboration with sighted instructors. As an example, while creating a threading sequence, Paul invited Leah (instructor) to provide more embodied support, saying *"Just drag my [hand] go like a mouse… tell me where to tap."* Thus, even when learning new concepts and interacting with a new technology, blind weavers had agency in defining the boundaries of guidance they received from sighted instructors. Furthermore, weavers thought that Simphony could help them take a more active part in the setup steps that are typically done by the instructors. Paul envisioned using Simphony to *"help out [the instructors to]… dress the loom, advance the loom."* He wanted to have Simphony *"incorporated into the looms"* to synchronize the 'dressing' routine (a pre-processing step) such that he would create and play threading sequences on the tablet while instructors would simultaneously lay out actual yarns on the loom and any mistakes in this process would be indicated with *"a buzzer noise."* Relatedly, Luke wanted to generate designs that would be less labor-intensive for the instructors, since he did not *"want to unduly burden"* them. As these examples begin to illustrate, blind weavers desired to use Simphony not only for enjoyment and learning but also to uphold and strengthen their interdependent, *"co-weaving"* relationships with sighted instructors in ways that would allow them to be in a position of giving support instead of always being on the receiving end [14, 37, 118].

## 9 DISCUSSION

Below we synthesize findings across our formative and design exploration studies to critically reflect upon how we might rethink multiplicity in understanding design within ability-diverse groups and what roles accessible technologies might play when incorporated into traditional forms of making.

### 9.1 Towards Multiplicity in Understanding Pattern Design

Creating accessible design tools requires understanding differences in how people with diverse abilities process information. In our study, we observed how blind and low-vision weavers and sighted instructors interpreted emergent shapes in fabric patterns differently due to the fundamental differences in visual, auditory, and tactile perception, echoing findings in other domains [29, 84, 92, 112]. Low-vision weavers and sighted instructors adopted a global approach by visually scanning the whole pattern and tracking the contour of emergent shapes. In contrast, blind weavers explored patterns sequentially by moving in a horizontal, vertical, or diagonal direction while attending to the auditory cues by tapping cells on the app or touching the grid with blocks. Weavers' methods of exploration [13, 85, 99], lived experiences with disabilities, and musical and mathematical knowledge, all influenced their "part-to-whole" comprehension of shapes [29, 63, 90, 92, 112]. However, expert blind weavers and sighted instructors emphasized that the goal is not to identify one 'correct' way of describing a pattern. The same woven pattern can lead to different understandings among blind, low vision, and sighted weavers based on their past experience and whether they explore a pattern on the tablet, with the blocks, on a fabric, or woven felt strips. Given this, Simphony illustrates the value of design tools that support a "multiplicity of meanings" [46, p.167] rather than promoting a singular understanding of patterns that are rooted only in sighted ways of knowing.

Moreover, understandings of pattern did not happen through technology or the material environment alone but through a collective process involving both blind and sighted collaborators. Blind weavers demonstrated sighted instructors how they *"made a cross (shape) with her hands"* (Leah) while running fingers over the blocks or tapping tablet cells. Instructors, in turn, guided the weavers along the contour of a shape they perceived visually through verbal explanations and/or hand-over-hand support. Our analysis highlights the mutual "care work" [18, 101] that makes such co-construction of meaning possible, in which both parties negotiated the boundaries of agency and assistance. Indeed, we observed instances when blind weavers decided whether or not they would like to receive more hand-over-hand guidance from sighted instructors in perceiving patterns. Bennett et al. [18] caution, however, that "even to care for another's access in a sight-dominant world—is to exert a politics, a politics for example of who has the authority to decide what bodies should guide other bodies..." Therefore, while foregrounding care work to enable shared meaning-making, we must be mindful of the possibilities of "non-innocent authorization of care" [18], given that instructors' position as sighted people with mastery of weaving knowledge creates a power asymmetry and puts them in the role of a caregiver and guide.

### 9.2 Accessible Design Technology as a Scaffold for Learning

Our analysis extends prior literature that integrates craftwork and interactive technologies (e.g., [8, 9, 20, 43, 52, 54, 114, 115]) by diving deeper into what it means to build an accessible design tool for making and crafting. In particular, we highlight how technologies can scaffold learning complex procedures for blind crafters, such as the underlying calculus of woven structures.

Generating pattern drafts is a complicated task that requires hands-on learning and practice, and even then, it can take years to master. Despite weaving for a long time, many blind weavers at the community studio found it difficult to grasp how their physical actions on the loom resulted in unique fabric patterns, partly due to their limited involvement in the design phase. In this regard, creating and exploring patterns first-hand on Simphony helped weavers learn and fill the gaps in their previous understanding of weaving concepts. Indeed, by reproducing the pattern he was weaving for his then active project, Luke was able to *"disconfirm [his prior] belief"* and develop new perspectives on the look and feel of the resulting pattern. For weavers like Lisa, who understood concepts better through metaphors and music—due to their expertise in music theory—Simphony formed the much needed "link" between abstract numerical sequences and what the sequence actually meant for weaving. Thus, Simphony supported weavers who needed *"more than just words"* for learning pattern design. The variety of representations introduced in Simphony, i.e., spoken audio, musical notes, instruments, colors, and tactile blocks, helped blind weavers and sighted instructors unveil individual learning styles and adapt their use of the interface to personalize the learning experience. Even when Simphony was "faded out" [104], i.e., removed from the workspace, Mark was able to retain and apply his understanding from the interaction with Simphony to troubleshoot an error he was encountering during a regular weaving session. Thus, technologies like Simphony could enable accessible ways of skill-building among blind learners. This finding aligns with prior work that built scaffolding systems for learning scientific concepts [48], programming [113], and everyday activities [134] among disabled children, but here we see that digital technologies can also be integrated as a scaffold in manual forms of making and crafting.

## 9.3 Accessible Technology as an Augmentation for Aesthetics and Performative Art

For our blind participants, fabrics are not only the outcomes of their weaving activities but also embodiment of their artistic thinking and imagination. Integrating Simphony into their workflow further prompted weavers to reimagine ways to break the boundaries between different art forms and add new dimensions to their fiber arts practices [20]. Not only colors and textures of yarns but now the sequences of weaving, with their unique musical progressions and instrumental presentation on Simphony, equipped blind weavers with new resources that they could manipulate to imbue fabrics with meaning. As an example, Adam inscribed melodies into his patterns by formulating threading sequences that followed note progressions of those melodies. Although prior work has explored how disabled people could track and display their moods by altering the form of textile swatches prepared by researchers [98], our work illustrates how blind weavers made use of Simphony to encode their emotions, stories, and favorite compositions into patterns through unique combinations of weaving sequences.

Previous work has investigated the performative potentials of fabrication [45] and crafting among sighted artists (e.g., SoundWeaving [125] and BeatWoven [70]). Our analysis, in contrast, centers the experiences of blind crafters and demonstrates how an accessible design tool like Simphony can move past its role as a mere functional aid and open up new avenues of performative art for blind people, evidenced by Jen, Luke, and Lisa wanting to perform musical renditions of their fabric patterns before an audience. This insight draws parallels to the ways disabled artists have explored technological and material augmentations to their assistive devices for performative art [12], for instance, by adapting a navigational cane as an instrument [128] and a ramp for wheelchair dance [105].

## 9.4 Limitations and Future Work

Our study is grounded in the needs and practices of this particular community studio where blind weavers work with and learn from sighted instructors. Although Simphony incorporates various audio-tactile cues to improve accessibility, it builds on visual rendering of patterns as done in traditional weaving drafts [72] and digital pattern drafting applications [2, 7] (e.g., by using colors in 2D grids). In this sense, our system also reinforces a vision-centric framing of pattern design. Future work should explore alternative non-visual ways of designing patterns (e.g., fully tangible systems or interactive textual descriptions [138]) to support blind weavers who work independently or teach other blind/sighted learners. Furthermore, we purposefully chose to develop a relatively low-cost solution including a digital application with a wooden grid and blocks instead of using more sophisticated and expensive devices. Future research may implement other emerging technologies such as refreshable tactile graphics displays [21, 103, 108] or 2.5D interactive shape displays [117] for accessible pattern design. Also, while we chose simple sonification techniques such as changing pitch and timbre to explore blind weavers' initial reactions to non-speech audio for representing patterns, future work may incorporate other auditory techniques like spearcons [78] and musicons [93]. Future work could also examine ways to generate complex patterns that span longer threading and treadling sequences and a higher number of shafts/treadles. For this, a 'panning' approach [21] could be adopted to demonstrate longer sequences or drawdowns part-by-part.

## 10 CONCLUSION

This study set out to enhance accessible pattern design practices within a community of blind weavers and their sighted instructors. Building upon our formative interviews, we developed Simphony, an audio-tactile system that incorporates a variety of sonification techniques, synthesized speech, a tactile overlay and wooden blocks to support blind weavers in generating and perceiving fabric patterns. Our design exploration study revealed the ways in which blind weavers made use of Simphony to create weaving sequences and understand interlacement structures and emerging shapes in fabric patterns. Through this, blind weavers also developed engaging and personalized learning opportunities with sighted instructors and reimagined artistic and aesthetic values of weaving. These insights encourage us to rethink what collaborative understanding of patterns constitutes in ability-diverse design teams and what roles technologies might play in transforming learning and access in collaborative making and crafting.

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