Exploring the Design of Audio-Kinetic Graphics for Education

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ABSTRACT

Creating tactile representations of visual information, especially moving images, is difficult due to a lack of available tactile computing technology and a lack of tools for authoring tactile information. To address these limitations, we developed a software framework that enables educators and other subject experts to create graphical representations that combine audio descriptions with kinetic motion. These audio-kinetic graphics can be played back using off-the-shelf computer hardware. We report on a study in which 10 educators developed content using our framework, and in which 18 people with vision impairments viewed these graphics on our output device. Our findings provide insights on how to translate knowledge of visual information to non-visual formats.

CCS CONCEPTS

• **Human-centered computing** → **User studies**; Audio-Kinetic Graphics;

KEYWORDS

Accessibility; Blindness; Non-Visual Interfaces; Tangible Interfaces; Education; Collaboration.

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1 INTRODUCTION

While there exist multiple ways to represent visual information non-visually, some information cannot be adequately represented

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Figure 1. A pen plotter, typically used to enable computer-aided drawing, is repurposed to provide tactile representations of shapes using kinetic motion. A user grips the mechanical arm to experience kinetic content.

using description alone. For example, while one may be able to describe the trajectory of a rocket through text alone, describing the physical path would greatly benefit from the use of a graphical representation. However, our computing technologies are currently quite limited in their ability to represent non-visual spatial information. We are especially limited in our ability to represent moving images, such as video and animation, in a non-visual format.

Spatial information is often key to conveying information in the classroom. Many domains, such as math, physics, art, and history, rely heavily on representing spatial information. Even when a classroom teacher is discussing something with low spatial information, such as describing a poem, the teacher may rely on non-verbal cues such as circling items on the whiteboard, or pointing at specific passages, to communicate an idea. Most, if not all, of this visual information is unavailable to blind students, who may struggle with educational content that is not presented in an accessible format [8].

Addressing the inaccessibility of visual content in education involves solving multiple challenging problems. On one hand, researchers must identify ways to render visual content using new technologies (e.g., FluxMarker [26], Linespace [27], iISO [17], and BrailleDis [28]), or find ways to repurpose existing technologies to support non-visual representations (e.g., using robots to create interactive tangible displays [10], and 3D printable accessible picture books [25]). Second, researchers must identify new tools and approaches to support the creation of non-visual content, and methods for adapting visual content to non-visual formats.

In this paper, we focus on exploring the translation between visual content, especially moving images, to non-visual and tangible image formats. We specifically examine issues of

translating educational content such as lecture materials. Rather than developing fundamentally new hardware for rendering tactile graphics, we repurpose an existing technology, a pen plotter, to render information about shape, size, and movement. We introduce a software tool, WeeGee, that enables users to create *audio-kinetic graphics* that contain an audio description plus information about a single point of movement. We use this prototype as a design probe to understand the translation between visual and non-visual representations, and to explore how blind and visually impaired individuals experience this non-visual, audio-kinetic information. To explore these questions, we conducted a study in which ten STEM educators adapted some visual concept into an audio-kinetic graphic using our software, and later presented a subset of these graphics to 18 visually impaired individuals.

The contributions of this paper include: introducing WeeGee, a hardware and software framework to convert pen movements and audio narration into a combined audio-kinetic graphic; experiments in using a pen plotter to render these audio-kinetic graphics; insights from a user study in which ten sighted educators attempt to convert visual concepts from their field into audio-kinetic graphics; and feedback from 18 visually impaired people about the experience of viewing these graphics.

2 RELATED WORK

2.1 Tangible Computing for Accessibility

Research in tangible user interfaces (TUIs) has primarily focused on the development of interfaces for interacting with digital information by actuating physical objects [14, 24]. These interfaces have been applied to many domains, including remote collaboration [7], data visualization [15], and web browsing [19].

Recently, researchers have investigated ways to use low-cost TUIs for assistive applications [9, 22, 23, 26]. Tangible Graph Builder [23] allows the visually impaired to construct and browse charts and diagrams using a tangible grid. FluxMarker [26] annotates static raised line tactile graphics with movable tactile markers providing a tangible interface for maps, graphs, and diagrams. Linespace [27] uses modified 3D-printer hardware to draw and erase tactile lines on a work surface. These interfaces are aimed at providing low-cost access to non-textual content, but little work has explored the use of these technologies for in-classroom education and online learning.

2.2 Access to Lecture Content

Classroom lectures can be highly visual featuring a variety of visual information, including presented slides, whiteboard drawings, visual aids, and gestures from the instructor. Thus, some lectures can present accessibility challenges for blind and visually impaired students, especially when covering material with high visual content, such as geometry, physics, and other STEM topics.

Some prior research has explored how in-classroom lectures can be made more accessible to people with various disabilities. Often these approaches use cameras in the classroom to capture

the instructor's movements. The Note-Taker [1] and Multi-View Platform [20] use cameras aimed at the instructor and her educational materials, such as a whiteboard or slides, to provide [13] access for low vision students. ClassInFocus [5] and Photonote used cameras in the classroom to show slides, whiteboard notes, and ASL interpreters in the same visual space. However, few tools exist to provide access to classroom interactions for blind students.

Other research has explored how to provide accessible auxiliary content for blind students. Much of this involves the creation of tactile graphics which can be useful for students with a range of visual abilities [11]. Recent work in this space has explored using Lego bricks [4], 3D printed images [2, 18, 25] and toy robots [9] to represent course materials. This work focusses on auxiliary content, which must be accompanied by an in-person or recorded lecture, rather than creating accessible versions of original lectures, as we do here.

2.3 Authoring Tools for Tactile Information

Even when an educator commits to creating a non-visual representation of their information, creating tactile graphics requires extensive skills and effort [16]. Prior research has explored how to automatically convert visual information to tactile formats, or to ease the process of converting between formats.

Researchers have looked at computer-aided methods for tactile graphics translations. Tools such as the Tactile Graphics Assistant (TGA) [21], the Graphics to Tactile project (G2T) [6], and others [12, 29, 30] make use of advanced image processing to automate the extraction of content, both visual and text, from digital graphics for rendering in tactile form. These systems have no support for customization of the translated tactile graphics and only G2T supports limited editing capabilities.

Other systems, like VizTouch [3], support custom creation of content-specific tactile graphics (e.g. graphics of mathematic functions and data sets), but cannot be more generally applied to other visual concepts. Recent research has looked at creating authoring frameworks for 3D tactile graphics. CraftML [31] is a structured programming language for creating 3D models that supports beginners and experts in making custom designs. Similarly, Stangl, et al. have investigated the skillsets needed to design 3D models and suggest the use of a collaborative design platform to unite designers from different disciplines to create meaningful 3D models [25]. These methods streamline the creation of tactile graphics and are less labor-intensive than traditional methods. However, these tools emphasize creating auxiliary materials as a process parallel to instruction, rather than adapting lecture materials directly into an accessible format.

3 WEEGEE: AUDIO-KINETIC GRAPHICS

In this section, we introduce WeeGee, a hardware-and-software prototype that supports *audio-kinetic graphics*, which combine audio narration with kinetic movement. In our system, the user holds a stylus which moves in two-dimensional space, providing a proprioceptive sense of motion. We explore this concept in the

context of representing video-based educational material, such as online lectures and MOOCs.

We consider this approach to be complementary to other approaches for representing educational content, such as image descriptions and static tactile graphics. Our approach has several distinct advantages over these approaches. First, audio-kinetic graphics can show static tactile information by drawing shapes in space but can also represent moving information. Second, by moving the stylus at different speeds, audio-kinetic graphics can display additional information, such as speed and acceleration. Third, audio-kinetic graphics can be used to quickly demonstrate tactile information, in contrast to traditional tactile graphics, which may take minutes or hours to print. Fourth, audio-kinetic graphics can be rendered using existing low-cost consumer hardware. Finally, audio-kinetic graphics can represent non-visual information such as pointing at specific locations or moving the user's hand to a specific point. This type of interaction, which is a key part of "chalk-and-talk" style lectures, serves as inspiration for the WeeGee project.

3.1 WeeGee Prototype

To explore the potential of audio-kinetic graphics for education, we developed a prototype system, called WeeGee in reference to its use of proprioceptive movement (as in the *Ouija* board game) and its physical resemblance to a squeegee (as shown in Figure 1). As there exist many prototypes for representing non-visual content, we do not consider the hardware itself to be a novel research contribution. Rather, we consider WeeGee to represent a novel method for combining off-the-shelf hardware, playback software, and authoring software, to create accessible educational content.

3.1.1 Hardware

Previous approaches to creating non-visual displays have often been limited by their extremely high cost, as in pin-array displays [7], or by their slow time to render graphics, as in traditional tactile graphic embossers and 3D printers. WeeGee attempts to balance these concerns using an off-the-shelf pen plotter, which is traditionally used for computer-controlled drawing. Our current prototype uses the AxiDraw V3 device from Evil Mad Scientist Labs. The AxiDraw costs about \$500US and can move any pen-sized object in an 8.5-by-11-inch work area. The AxiDraw moves at a speed of up to 11 inches per second, with a precision of 0.005 inches. Force is not reported in the specifications; in practice, we have found that it provides sufficient force to guide the hands of our test users. The pen has the ability to move up 0.7 inches from the drawing surface. The device itself is reasonably portable at 32.5 by 16 by 4 inches and weighs 5.75 pounds.

We chose the AxiDraw hardware due to its low cost and large work area. However, the WeeGee system could be extended to support many different types of pen plotter devices, from larger industrial devices to small, inexpensive do-it-yourself device kits.

3.1.2 Playback Software

Out of the box, the AxiDraw hardware is controlled through plugins to the Inkscape vector drawing program, accepting a

vector drawing as input and controlling the movements of the pen. To support WeeGee's real-time movement, we developed a desktop application for controlling the pen plotter hardware, including moving to specific points, drawing shapes, and syncing playback with audio recording. This software was developed for Windows 10 using C# and communicates with the device over USB.

3.1.3 Authoring Software

Teachers of the visually impaired (TVIs) often communicate with their students by holding their hand and moving it over some object. For example, when teaching a blind student about a campus map, a TVI might move their student's hand to various points of interest while describing each one. WeeGee's interaction model is inspired by this type of tactile learning, as well as the kind of whiteboard-sketch-driven education used in many STEM classes, and online educational videos such as those of Khan Academy. WeeGee's authoring software is specifically designed to support teachers who wish to make their content accessible but lack formal training in creating tactile graphics.

The primary method for authoring WeeGee content is through pen input using a touch screen device and stylus, such as a Microsoft Surface tablet. WeeGee's authoring tool takes the appearance of a blank page. The author begins a recording and can then draw strokes into the window using the stylus. In addition, the author may talk during their recording, or may use recorded audio from another source, such as a pre-recorded video lecture. The author may open up another window, such as a video, and play it back while recording their WeeGee lecture (Figure 2).

The system generates the graphics by recording the stylus movements as timestamps and x, y positions at XY millisecond intervals. This data is stored in a comma-separated file. On playback, WeeGee decodes the timestamps and locations to synchronize movement and audio. Synchronization between audio and pen plotter movement depends on the author's drawings speed when authoring audio-kinetic graphics.

Figure 2. WeeGee's authoring tool enables an author to watch an existing video (from Khan Academy, right) while sketching a tactile representation of that content (left).

WeeGee's authoring tool is meant to follow WYSIWYG principles wherever possible. The author moves their stylus and narrates (or plays back audio), and later the system plays the same audio, and moves the pen plotter at the same speed and to the same location as the author's sketches. We have also experimented with the use of ink colors to represent different types of pen plotter movements: for example, an author can draw

a red line, which would then move the pen plotter in a dashed motion. WeeGee supports a live playback mode, in which the pen plotter is synchronized with the real-time movements of the pen. However, we omitted both of these features from our present study, and intend to explore them in future studies.

4 EVALUATION WITH INSTRUCTORS

We intend WeeGee to be usable by educators who wish to provide accessible versions of their lectures, but who may lack formal training in accessibility or tactile graphics. To explore the opportunities and challenges of recording accessible lectures with WeeGee, we conducted a preliminary study with 10 college educators who currently teach in STEM-related fields. The goal of this study was to identify what topics in each instructor's field are difficult to convey without visual feedback, to determine whether these concepts might be expressed non-visually using WeeGee's authoring tools, and to identify usability challenges with the existing WeeGee prototype.

Each evaluation session lasted approximately 30 minutes. During the session, the research team introduced the instructor to the concept of the WeeGee prototype and played back a demonstration lecture. The researchers then asked the instructor to think through which types of content might be difficult to understand for a blind student, and to consider how these concepts might be represented using WeeGee. Finally, the researchers asked each instructor for feedback about the WeeGee prototype.

4.1 Choosing Educational Concepts

We asked instructors to consider topics and concepts in their field that might be difficult to understand for a blind student who cannot follow along with the visual representation, but that might be successfully represented by WeeGee.

Instructors chose a variety of topics relevant to their field, including biology, chemistry, computer science, economics, music theory, design, and history. Specific examples include demonstrating distributions of data, representing nodes in physics, tracing the flow of electricity through a circuit, and representing how a violin makes sound based on the speed and angle of the bow's movement. Some educators referenced static images, such as charts and diagrams, while others referenced animations and moving data.

4.2 From Ideas to Audio-Kinetic Graphics

After choosing an idea, instructors used the WeeGee authoring tool to implement their topic. They were allowed to search for source material to adapt, or to create their representation from scratch. For audio, they were allowed to use audio from their source material, provide their own narration, or use a combination of prerecorded audio and original narration. We encouraged the instructors to break down complex ideas into smaller chunks, drawing between 1 and 5 objects at a time. Because this was the instructors' first time using this type of tool, we encouraged the instructors to test out their ideas until they were satisfied with the end result.

In general, the instructors expressed satisfaction with the end result. However, they described some challenges that were particular to adapting their lecture content to audio-kinetic format:

Ordering. In some cases, instructors wished to draw several shapes at the same time. Because WeeGee shows only a single point that moves over time, drawing shapes using WeeGee imposes an order to how those shapes will be rendered, and thus the order in which they will be presented. Instructors sometimes reported that the order in which multiple shapes were drawn did not reflect the optimal order for representing those shapes, and thus they would like to have the ability to easily draw and reorder shapes.

Sequencing audio and kinetic content. When annotating videos, instructors sometimes struggled to synchronize the audio and kinetic motion. When translating from a visual to an audio-kinetic representation, the instructors often found that the audio-kinetic representation was slower, especially because objects needed to be presented one at a time, and because of the need to point at or emphasize different objects. Thus, especially when adapting existing content, the instructors expressed a need to slow down or pause the source material to keep the audio and kinetic components in sync.

Representing points and grouping. In addition to representing shapes, instructors sometimes wished to represent a single point. It is not immediately obvious how to represent a point with WeeGee, as it is difficult to distinguish when the pen plotter is drawing a point or simply standing still. To address this, one instructor drew small circles to represent points. Another instructor used a circle around the page to refer to a group of "all" items. In these cases, there may be some ambiguity between when WeeGee is "drawing" and when it is "pointing." This ambiguity may be addressed by providing multiple drawing modes, with different motion characteristics, as we explored in the following user study.

Despite these limitations, the instructors were enthusiastic about their creations and felt that they could use WeeGee to create accessible representations of their content.

4.3 Suggested Enhancements

When asked how WeeGee might be improved, instructors offered several suggestions. First, the instructors requested more control over editing playback, including reordering the drawing of shapes, and slowing down or speeding up playback to match source material. Second, because drawing shapes freehand was sometimes difficult, instructors requested the ability to "clean up" drawings, or the ability to use pre-defined shapes and symbols.

5 EVALUATION WITH BLIND USERS

To evaluate the effectiveness of WeeGee at conveying non-visual content and to identify how to optimize WeeGee's movement for optimal legibility, we conducted a user study in which blind adults explored audio-kinetic graphics using the WeeGee prototype and the AxiDraw V3 pen plotter described previously.

Figure 3. Audio-kinetic graphic for the video *Properties of a Circle*.¹

5.1 Participants

We recruited 18 individuals with visual impairments (13 male, 5 female, aged 23 to 65) from an assistive technology conference. Of these participants, 9 had been blind or visually impaired since birth and 9 had been blind or visually impaired for at least 10 years. All participants used a screen reader and 14 were fluent in Braille.

All participants had prior experience using traditional, paper-based tactile graphics, and all had experience with a human teacher guiding their hands over a tactile graphic. Seven participants had previously used tactile 3D models for learning. Ten participants worked in engineering or assistive technology, but all reported being familiar with computing technology.

5.2 Procedure

We conducted a 30-minute study session with each participant in which they viewed audio-kinetic graphics created specifically for the study. At the start of the session, we introduced the goals of the WeeGee system and how it might be used to create audio-kinetic graphics for educational purposes. We introduced the AxiDraw hardware and showed how the pen plotter can be used to draw lines and shapes. At this time, participants chose the drawing speed as we found in pilot testing that they had

Figure 4. Audio-kinetic graphic for the video *Standing Waves*.²

preferences for different speeds. Drawing speeds ranged from 4 to 9 inches per second with 7 inches per second being chosen most often. The drawing speed was the same for the stroke transition and shape recognition tasks.

Following this introduction, participants completed a set of four tasks: the *transition recognition* and *stroke recognition* task, and two *lecture content* tasks, described below. As each task introduced new concepts that built upon the previous task, the order of these tasks was the same for all participants. Due to time constraints, 14 of the participants completed both lecture tasks, and 4 completed only the first task. Following these tasks, participants completed an interview in which they provided feedback about their experience.

Stroke Transition Task. In our pilot study, we saw that identifying transitions between shapes could sometimes be difficult. In this task, we presented the same graphic, consisting of three basic shapes, with three different techniques for separating the shapes (Figure 5). The transition techniques were:

- **Vertical lift:** When drawing a shape, the pen rested just above the table surface. When moving between shapes, the pen raised approximately half an inch off the surface.
- **Dashed movement:** When drawing a shape, the pen moved in a smooth motion. When moving between shapes, the pen moved in an irregular, halting motion, representing a dashed line.

¹ Khan Academy Physics. (2009, November 8). *Circles: radius, diameter, circumference and Pi* [Video file]. Retrieved from <https://www.youtube.com/watch?v=jyLRpr2P0MQ&t=95s>.

² Khan Academy Physics. (2016, July 29). *Standing waves on strings* [Video file]. Retrieved from <https://www.youtube.com/watch?v=jyLRpr2P0MQ&t=91s>.

- **Sonification:** When drawing a shape, the system played a continuous tone. When moving between shapes, the system made no sound.

Figure 5. Shapes used in the stroke transition task.

Participants were presented with the three shapes shown in Figure 5. The three transition types were presented once in random order. For each transition, the shapes were drawn in a random order. After each example, participants were asked to describe the shapes they experienced. At the end of this task, participants were asked to describe their preferred transition method(s).

Shape Recognition Task. One requirement for creating a non-visual display is the ability to render recognizable shapes [26, 9]. To explore how blind persons make sense of WeeGee's output, we asked participants to describe a complex shape rendered by WeeGee: a five-pointed star, drawn at one inch in size. The shape was first drawn at 6 inches per second. If the participant could not correctly identify the shape, it was drawn up to twice more at half speed. If the participant was still unable to identify the shape, the researcher described the shape and demonstrated it once more.

Lecture Content Task. Following the two test tasks, participants interacted with two complete lectures. These two lectures were created by the research team and were adapted from videos originally posted on Khan Academy. The narration for these audio-kinetic graphics was taken directly from the source videos. We chose these videos as they were longer and more complex than those created by instructors during the first study, and because they were more representative of the content that might be produced by a skilled author using WeeGee.

The first video lecture (Figure 3) gave an overview of the properties of a circle and focused on spatial layout. The lecture described three core properties, the center, the radius, and the diameter of a circle. It lasted 2 minutes and 30 seconds.

The second video lecture (Figure 4) explained the physics of a standing wave and explored spatiotemporal motion. The lecture described the pattern created within a medium when the vibrational frequency of a source causes waves to reflect from one end of the medium to interfere with incident waves from the source. The lecture lasted approximately 3 minutes.

6 FINDINGS

6.1 Recognizing Transitions

We asked participants to describe their preferred transition method and to provide feedback about each method. Fifteen participants chose the vertical lift transition as their favorite. It was considered to be most intuitive and was easy to differentiate from other movement. One participant praised the "smooth transitions of the vertical movement." A participant also noted: "Z movement is most intuitive because it's analogous to what you would do drawing."

Three participants preferred the dashed movement transition, as it was easy to recognize, and the pauses in the movement helped focus on the shapes. However, some participants found the movement itself to be unpleasant or confusing. One participant stated, "With the dashes it is hard to tell where the shape ends." Four participants also noted that dashed movement took longer to convey a transition than vertical lift movement.

No participants preferred the sonification transition. One participant described how the noise of the pen plotter interfered with the sonification sounds, stating "[the] audio confused me because the motors are also making noise."

6.2 Recognizing Shapes

After experiencing the shapes and transitions, we asked participants to identify the shape of the five-pointed star. Seven participants correctly identified the star on their first attempt and five identified it on their second or third viewing. Those who did not identify the star guessed an asterisk, pentagon, rose bud, or two overlapping triangles. Two participants were unable to guess any shape.

When asked to describe their process for recognizing the shape, participants mentioned counting the points or the changes in direction. One participant, who struggled to identify the shape, stated that he "was not sure if the corners were sharp or rounded," and suggested adding a stop at each point.

6.3 Experiencing Lecture Content

We asked participants to rate their overall experience using WeeGee on a five-point scale: "very poor", "poor", "OK", "good", and "very good." On average, participants rated the experience as "good" (4 "very good", 11 "good", and 3 "OK"). Participants cited several benefits to using audio-kinetic graphics. The major themes of users' feedback are summarized here.

Directing attention. Participants commented that the kinetic motion aided in understanding by moving the user's hand toward the location of interest. One participant stated, "It definitely made it easier to understand what the lecturer was visually pointing out on the board" and another participant said, "I was able to understand everything, especially when [the lecturer] said 'here and here.'" One participant noted, "I liked the motion together with the lecture because it emphasizes the important content."

Several participants expressed that it was helpful to have the content presented to them, rather than having to actively explore tactile content to make sense of it. The synchronization of audio with the kinetic motion helped participants follow the lecture content step-by-step. To summarize his experience, a participant stated, "this would be a great adjunct to a live presentation."

Effectiveness of kinetic representation. In some cases, participants expressed that the lecture material was more effectively transmitted through motion than through a static tactile or audio representation. One participant noted that kinetic motion was "far more effective than trying to feel a string or a raised line to demonstrate a wave." Another participant stated, "This was really meaningful because I am always making a picture in my head, so this assists in making that picture."

Five participants pointed out that the kinetic representation specifically helped in understanding cause and effect. One participant stated, “The idea that waves are going back and forth and reflecting on each other was represented really well.”

Overall, participants seemed to find the kinetic representation enjoyable. One participant said, “I liked the amount of information that was conveyed with the motion. It was sufficient, but not excessive.” Another participant noted that the apparatus was “not moving too much so it is not distracting.” However, some participants noted that the representations tested in the study were relatively simple, and that they would need further practice to be able to recognize more complex shapes, make precise measurements, or make comparisons between multiple objects.

Synchronization of kinetic and audio content. Three participants praised the synchronization between the audio narration and kinetic content. A participant noted, “one thing I have really struggled with is when a professor throws something on the board and I have to go find the tactile diagram and then I am not even sure I am looking at the right tactile diagram because they don’t describe it well.”

Responsiveness. Participants commented that WeeGee’s ability to quickly represent tactile content could be useful in many educational situations. One participant stated, “I like that I can see the results right away.”

Seven participants noted the usefulness in being able to create audio-kinetic graphics in real time. One participant noted, “This representation can be done quickly enough so that it can be done real-time which is really unique and helpful in understanding the material.” WeeGee’s rapid feedback could lead to improved learning outcomes and might increase engagement, as one participant described: “I felt much more engaged, like, ‘what’s going to happen next?’” Participants noted that this rapid feedback would allow a student to ask questions during the lecture, rather than following along behind the rest of the class.

Reusability. Participants noted that, unlike an embossed or 3D-printed tactile graphic, WeeGee could be used to represent many images in a single object.

Independence. One participant mentioned that WeeGee was “almost like a real person’s hand” in its ability to guide the user. Conversely, WeeGee provided this capability to the user on his or her own. As one participant noted, WeeGee “can be used at home without other help.”

6.4 Usability Challenges

Although participants were enthusiastic about using the WeeGee prototype, we observed some usability issues during the study. Due to the small size of the pen and the rapid movement of the pen plotter, participants sometimes needed to adjust their grip on the plotter during movement, and in several cases lost their grip. Some participants compensated for this challenge by gripping the device with a second hand. This problem was exacerbated when the user did not expect the plotter to start moving, which occurred when video content featured long pauses followed by sudden movement. One participant noted, “I would lose grip of the thing because I didn’t know when it was going to move.” This problem might be addressed in the future by providing a cue when the

plotter is about to move, by providing a more ergonomic grip, or by more gently easing from stationary position into motion.

In addition to losing grip of the device, several participants expressed the desire to pause or rewind playback. During the study, participants were occasionally interrupted and let go of the pen plotter for a few seconds. Because users currently cannot pause playback, it was difficult to grasp the plotter again and participants sometimes lost their place during this interruption.

6.5 Participant Feedback

Participants proposed a number of improvements to the WeeGee prototype. They requested that the device motors be made quieter so that it could be used in the classroom and suggested making the device smaller and less bulky. One participant said, “It would be great if [WeeGee] could fit in my backpack.”

Ten participants asked for a way to rewind, fast forward, and pause playback, and other participants requested the ability to zoom in and out of content, or to adjust the level of detail.

Three participants suggested combining audio-kinetic graphics with traditional tactile graphics. A participant stated, “It would be nice to have some offline [static tactile] representation.” Comparing traditional tactile graphics to audio-kinetic graphics, another participant said, “I want the best of both worlds. I want the motion and some kind of medium underneath it.”

We asked participants what content they would like to view using WeeGee. Thirteen participants mentioned STEM related diagrams and charts. Seven participants mentioned using WeeGee to demonstrate sequential processes and instructions, such as walking directions. Two participants suggested that WeeGee could illustrate movies or TV shows, and one participant suggested using WeeGee to create audio-kinetic puzzle games.

When asked how else they might use this device, 9 participants suggested using WeeGee to participate in online classes or workshops, 11 participants mentioned use around the home, 4 suggested using WeeGee to read maps on the go, 2 participants suggested about using WeeGee to teach floor plans of buildings, and other participants suggested uses such as an alternative game controller to play games, as a means to analyze and understand stock market graphs, and to collaborate with sighted co-workers.

7 DISCUSSION

Both teachers and blind end users responded positively to the WeeGee prototype and its representative audio-kinetic graphics. Feedback from the two user studies and our design of the WeeGee prototype has raised a number of questions about the challenges and opportunities of creating audio-kinetic graphics.

7.1 Understanding Audio-Kinetic Graphics

Our user study showed clear trends in how blind users made sense of audio-kinetic graphics. To identify a shape, participants often counted the number of changes in direction, and tracked the location and curvature of each direction change. Tracking changes was found to be more difficult at higher speeds and as the number of inflection points increased.

In many cases, participants were able to accurately count the inflection points but mistook the curvature of those points, confusing a star with a flower shape, or mistook the aspect ratio of a shape, confusing a square with a rectangle. Participants suggested that these confusing aspects might be made clearer by drawing more attention to speed and direction changes, such as by slowing down or pausing before each inflection point.

One question that we had in WeeGee's development was how to delineate different objects and to separate "drawing" shapes from moving between shapes. Our user study showed that the AxiDraw's vertical movement was clearly interpreted as a mode switch and can be used effectively to move the pen around the work area without confusing the user. As some plotters may not have the capability to move in the Z-axis, similar systems may need to rely on other methods to delineate shapes. One method for doing so that was suggested by our participants is to pause drawing; in general, participants understood pauses to represent a shift in the current mode, or a transition between different shapes.

7.2 Requirements for Audio-Kinetic Graphics

Participants' appraisal and criticism of audio-kinetic graphics provided insights into the requirements for kinetic representations of non-visual content. Participants commended the synchronization of speech with movement to make sense of verbal and physical references. Participants felt it was important to be in sync with the lecturer to stay engaged in the presentation and to be able to ask relevant questions. As the hearing sense has greater bandwidth than touch, kinetic motion has to be succinct and should augment speech – not vice versa. Participants perceived the kinetic motion as indicating concepts of particular importance and as an aid to understand dynamics not easily expressed in words.

As determining the number and location of inflection points is key to differentiating between shapes, inflection points should be highlighted. Participants felt that pausing on each inflection point assisted in identifying the number of nodes and edges of a shape. Similarly, cuing for movement can help users focus on the task of parsing the sequences of motion.

Lastly, participants confirmed that it is imperative to clearly differentiate between movement intended to represent a shape and movement intended to represent a transition or a reference point. Using vertical movement similar to lifting a pen off paper, allowed participants to quickly identify the end of a shape and the beginning of a transition or movement to a reference point.

7.3 Creating Audio-Kinetic Content

Audio-kinetic graphics can be used to unambiguously represent content that has some inherent sequence such as biological processes, content that can be broken down into multiple, smaller representations such as the behavior of matter through space and time, and spatiotemporal patterns such as planetary orbits. It is difficult to represent multiple objects and multiple relationships between objects simultaneously. Even when limiting the number of shapes, it is challenging to represent compound shapes or

overlapping shapes because audio-kinetic graphics are depicted on a 2D plane. Users can use the hands as reference points to compare different parts of the audio-kinetic graphic but are physically and cognitively limited to a finite number of reference points. Also, it is difficult to compare the exact and relative magnitude of shapes as dimensional variations between shapes are indistinct.

8 FUTURE WORK

The WeeGee prototype represents our first attempt at building a comprehensive system for authoring, distributing, and playing audio-kinetic graphics. Based on our work to date, we identify several opportunities for improving the system. First, we should provide enhanced controls for playing back content, including pausing, skipping, and controlling playback speed. These controls would be especially useful for long videos or online courses and for repeatedly viewing and studying the same content.

We can also make use of pen plotters' 3D capabilities to enhance WeeGee's expressiveness of more complex geometric relationships. By moving in the Z-axis, we can represent overlapping shapes, groups of shapes, inscribed shapes, and others.

We also see opportunities in combining WeeGee's proprioceptive motion control with static tactile graphics, providing a static frame of reference that the user can feel beneath the stylus. This could be achieved by combining WeeGee's pen with 3D-printing or raised-line-drawing capability, or by providing a way to overlay an embossed tactile graphic.

A fourth opportunity for enhancing WeeGee is to improve authoring of audio-kinetic content through new authoring tools and tools to automatically or semi-automatically convert visual content to audio-kinetic graphics. Specifically, we imagine augmenting the AxiDraw with a tracking device to measure manual movement of the arm. Manual control would allow users to author kinetic graphics and control playback by directly manipulating the pen plotter.

In addition to improving WeeGee's ability to create tactile graphics, we see opportunities to use this platform to explore the process of creating and sharing tactile graphics, and to explore how visual content is best transformed into tactile and kinetic forms.

9 CONCLUSION

While non-visual representations of graphical information can be useful to blind and visually impaired learners, it is difficult to author and distribute non-visual representations of graphical information, especially moving images. We introduced WeeGee, a system that enables online lectures to be authored and shared with blind learners. WeeGee's authoring tools enable educators to represent concepts non-visually through a combination of speech and motion. Through our formative evaluations with sighted teachers and blind learners, we show that spatial information such as online lecture content can be authored and shared online and represented non-visually using off-the-shelf hardware.

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REFERENCES

- [1] Black, J. A., & Hayden, D. S. (2010, June). The Note-Taker: An assistive technology that allows students who are legally blind to take notes in the classroom. In *Computer Vision and Pattern Recognition Workshops (CVPRW)*, 2010 IEEE Computer Society Conference on (pp. 1-8). IEEE.
- [2] Braier, J., Lattenkamp, K., Räthel, B., Schering, S., Wojatzki, M., & Weyers, B. (2015). Haptic 3D surface representation of table-based data for people with visual impairments. *ACM Transactions on Accessible Computing (TACCESS)*, 6(1), 1.
- [3] Brown, C., & Hurst, A. (2012, February). VizTouch: automatically generated tactile visualizations of coordinate spaces. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction* (pp. 131-138). ACM.
- [4] Capovilla, D., Krugel, J., & Hubwieser, P. (2013, March). Teaching algorithmic thinking using haptic models for visually impaired students. In *Learning and Teaching in Computing and Engineering (LaTiCE)*, 2013 (pp. 167-171). IEEE.
- [5] Cavender, A. C., Bigham, J. P., & Ladner, R. E. (2009, October). ClassInFocus: enabling improved visual attention strategies for deaf and hard of hearing students. In *Proceedings of the 11th international ACM SIGACCESS conference on Computers and accessibility* (pp. 67-74). ACM.
- [6] Crombie, D., Lenoir, R., McKenzie, N., & Ioannidis, G. (2004, July). The bigger picture: Automated production tools for tactile graphics. In *International Conference on Computers for Handicapped Persons* (pp. 713-720). Springer, Berlin, Heidelberg.
- [7] Follmer, S., Leithinger, D., Olwal, A., Hogge, A., & Ishii, H. (2013, October). inFORM: dynamic physical affordances and constraints through shape and object actuation. In *Uist* (Vol. 13, pp. 417-426).
- [8] Freire, A. P., Linhalis, F., Bianchini, S. L., Fortes, R. P., & Maria da Graça, C. P. (2010). Revealing the whiteboard to blind students: An inclusive approach to provide mediation in synchronous e-learning activities. *Computers & Education*, 54(4), 866-876.
- [9] Guinness, D. (2018). Using robots to improve the accessibility of online videos. *ACM SIGACCESS Accessibility and Computing*, (120), 20-23.
- [10] Guinness, D., Szafir, D., & Kane, S. K. (2017, June). GUI Robots: Using off-the-shelf robots as tangible input and output devices for unmodified GUI applications. In *Proceedings of the 2017 Conference on Designing Interactive Systems* (pp. 767-778). ACM.
- [11] Hornecker, E., & Buur, J. (2006, April). Getting a grip on tangible interaction: a framework on physical space and social interaction. In *Proceedings of the SIGCHI conference on Human Factors in computing systems* (pp. 437-446). ACM.
- [12] Horstmann*, M., Lorenz, M., Watkowski, A., Ioannidis, G., Herzog, O., King, A., ... & King, N. (2004). Automated interpretation and accessible presentation of technical diagrams for blind people. *New Review of Hypermedia and Multimedia*, 10(2), 141-163.
- [13] Hughes, G., & Robinson, P. (2007, October). Photonote evaluation: aiding students with disabilities in a lecture environment. In *Proceedings of the 9th international ACM SIGACCESS conference on Computers and accessibility* (pp. 99-106). ACM.
- [14] Ishii, H., & Ullmer, B. (1997, March). Tangible bits: towards seamless interfaces between people, bits and atoms. In *Proceedings of the ACM SIGCHI Conference on Human factors in computing systems* (pp. 234-241). ACM.
- [15] Jacobsson, M., Fernaeus, Y., & Holmquist, L. E. (2008). Glowbots: Designing and implementing engaging human-robot interaction.
- [16] Jayant, C., Renzelmann, M., Wen, D., Krisnandi, S., Ladner, R., & Comden, D. (2007, October). Automated tactile graphics translation: in the field. In *Proceedings of the 9th international ACM SIGACCESS conference on Computers and accessibility* (pp. 75-82). ACM.
- [17] Jeon, M., Smith, M. T., Walker, J. W., & Kuhl, S. A. (2014, June). Constructing the immersive interactive sonification platform (iSoP). In *International Conference on Distributed, Ambient, and Pervasive Interactions* (pp. 337-348). Springer, Cham.
- [18] Kane, S. K., & Bigham, J. P. (2014, March). Tracking @stemxcomet: teaching programming to blind students via 3D printing, crisis management, and twitter. In *Proceedings of the 45th ACM technical symposium on Computer science education* (pp. 247-252). ACM.
- [19] Kelly, R. (2000). Working with WebQuests: Making the web accessible to students with disabilities. *Teaching Exceptional Children*, 32(6), 4-13.
- [20] Kushalnagar, R. S., Ludie, S. A., & Kushalnagar, P. (2011, October). Multi-view platform: an accessible live classroom viewing approach for low vision students. In *The proceedings of the 13th international ACM SIGACCESS conference on Computers and accessibility* (pp. 267-268). ACM.
- [21] Ladner, R. E., Ivory, M. Y., Rao, R., Burgstahler, S., Comden, D., Hahn, S., ... & Martin, A. (2005, October). Automating tactile graphics translation. In *Proceedings of the 7th international ACM SIGACCESS conference on Computers and accessibility* (pp. 150-157). ACM.
- [22] Manshad, M. S., Pontelli, E., & Manshad, S. J. (2011, October). MICOO (multimodal interactive cubes for object orientation): a tangible user interface for the blind and visually impaired. In *The proceedings of the 13th international ACM SIGACCESS conference on Computers and accessibility* (pp. 261-262). ACM.
- [23] McGookin, D., Robertson, E., & Brewster, S. (2010, April). Clutching at straws: using tangible interaction to provide non-visual access to graphs. In *Proceedings of the SIGCHI conference on human factors in computing systems* (pp. 1715-1724). ACM.
- [24] Pangaro, G., Maynes-Aminzade, D., & Ishii, H. (2003). The actuated workbench: computer-controlled actuation in tabletop tangible interfaces. *ACM Transactions on Graphics*, 22(3), 699-699.
- [25] Stangl, A., Hsu, C. L., & Yeh, T. (2015, October). Transcribing across the senses: community efforts to create 3D printable accessible tactile pictures for young children with visual impairments. In *Proceedings of the 17th International ACM SIGACCESS Conference on Computers & Accessibility* (pp. 127-137). ACM.
- [26] Suzuki, R., Stangl, A., Gross, M. D., & Yeh, T. (2017, October). FluxMarker: Enhancing Tactile Graphics with Dynamic Tactile Markers. In *Proceedings of the 19th International ACM SIGACCESS Conference on Computers and Accessibility* (pp. 190-199). ACM.
- [27] Swaminathan, S., Roumen, T., Kovacs, R., Stangl, D., Mueller, S., & Baudisch, P. (2016, May). Linespace: A sensemaking platform for the blind. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (pp. 2175-2185). ACM.
- [28] Völkel, T., Weber, G., & Baumann, U. (2008, July). Tactile graphics revised: the novel brailledis 9000 pin-matrix device with multitouch input. In *International Conference on Computers for Handicapped Persons* (pp. 835-842). Springer, Berlin, Heidelberg.
- [29] Wang, Z., Li, B., Hedgpeth, T., & Haven, T. (2009, October). Instant tactile-audio map: enabling access to digital maps for people with visual impairment. In *Proceedings of the 11th international ACM SIGACCESS conference on Computers and accessibility* (pp. 43-50). ACM.
- [30] Way, T. P., & Barner, K. E. (1997). Automatic visual to tactile translation. II. Evaluation of the TACTile image creation system. *IEEE Transactions on Rehabilitation Engineering*, 5(1), 95-105.
- [31] Yeh, T., & Kim, J. (2018). CraftML: Where 3D Modeling is Web Programming.