Understanding the Opportunities For Introducing Multimodal Tactile Graphics in Classrooms

by

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DEDICATION

To अण्णा and आई.

For their unlimited confidence in me, even when I stumbled.

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Finally, the time has come for me to express my heartfelt gratitude—a moment I have eagerly awaited. It's true what they say—it takes a village to achieve great things, and my village has been nothing short of incredible.

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TABLE OF CONTENTS

LIST OF FIGURES

FIGURE

LIST OF TABLES

TABLE

LIST OF APPENDICES

LIST OF ACRONYMS

BVI Blind and Visually Impaired

ECC Expanded Core Curriculum

IEP Individualized Education Plan

ISD Intermediate School Districts

O and M Orientation and Mobility

OT Occupational Therapists

PEO People-Environment-Occupation model

T3TF T3 Task Flow

TG Tactile Graphics

TPACK Technological Pedagogical and Content Knowledge framework

TTF Tactile Task Flow

TVI Teachers of Students with Vision Impairments

UDL Universal Design for Learning

ABSTRACT

Tactile graphics convert visual information into touchable patterns and braille, providing an essential solution for accessible graphics for individuals with visual impairments. Pioneering research advocates for the potential of audio-augmented tactile graphics, which convey complex information through auditory and tactile modalities rather than touch alone. Despite recognizing their advantages, there is a significant lack of knowledge on how educators can effectively produce and implement these tools to achieve specific educational goals. Addressing this gap is crucial for the widespread adoption of audio-tactile graphics in education.

This thesis presents three studies that investigate different aspects of this gap, focusing on the integration of audio-tactile graphics within educational contexts that traditionally rely solely on tactile graphics:

Study 1 evaluates workplace factors that impact transcription workflows at educational institutions and transcription agencies, including tool selection for creating tactile graphics. It uncovers the socio-technical dynamics that influence the transcription process, such as the interaction between transcription teams and external stakeholders like classroom teachers and students, as well as internal organizational structures. The study reveals that while common tools are used across settings, distinct workflows and structural differences greatly affect the transcription approach. Insights from this study are crucial for developing tactile graphics and authoring tools that cater to the specific needs of different transcription contexts.

Study 2 narrows the focus to the educational setting, investigating how educators can translate visual images into audio-tactile graphics using their existing resources. A co-design workshop engages educators in simulating an improvised transcription process, resulting in the creation of T3 graphics. These graphics support educational goals such as facilitating tactile exploration and promoting independent reading in novice learners. Discussions highlight how the adoption of T3 graphics could significantly redefine job roles, extend the transcription process, require new training, and introduce complementary teaching methods. These findings indicate the potential of audio-tactile graphics to enhance educational outcomes and outline key areas for their practical implementation in schools.

Study 3 assesses the real-world application of the T3 tablet in educational settings,

examining the pedagogical strategies that educators employ with audio-tactile graphics in the classroom. The study observes that the proposed workflow for T3 graphics seamlessly integrates with existing methods of creating traditional tactile graphics. Over a period of six weeks, educators demonstrate how the T3 supports diverse educational tasks (like exams, classroom instruction and homework), supporting both traditional and novel teaching methodologies. Notably, the T3 proves to be an effective tool in promoting independent reading among beginners and in creating intricate, interactive tactile graphics. These findings suggest that audio-tactile devices like the T3 have the potential to play a crucial role in educational strategies, transforming the teaching strategies if educators had access to audio-tactile graphics as part of their instruction toolkit.

The thesis makes the following core contributions: 1) A workflow for creating audio-supported tactile graphics that aligns with current transcription practices for traditional tactile graphics in schools. 2) Design recommendations for audio-tactile graphics to help visually impaired students navigate information with greater independence and proficiency. 3) Innovative teaching methodologies derived from educators' experiences with audio-tactile tools in the classroom and orientation & mobility (O&M) exercises that meet the education outcomes of teachers of visually impaired students. These contributions collectively enhance our understanding of the role of audio-tactile graphics in educational settings and provide a foundation for their further development and long-term adoption in educational contexts.

CHAPTER 1

Introduction

The 4th goal of the United Nations Sustainable Development Agenda underscores the importance of "quality education." It is dedicated to "ensuring inclusive and equitable high-quality education and fostering opportunities for lifelong learning for all" [170]. An essential target of this objective is to "eliminate gender disparities in education and ensure equal access to all levels of education and vocational training for the vulnerable, including persons with disabilities, indigenous peoples and children in vulnerable situations." Ensuring equitable access to highest quality of education worldwide is crucial because it lays the cornerstone for crafting a society that is inclusive, just, and geared towards sustainable advancement. The academic and professional trajectories of students are inextricably linked to their equitable access to education, more so for students with disabilities [174, 215]. Numerous studies have drawn a direct correlation between a decline in academic performance and the lack of proper accommodations [108, 202]. With STEM education progressively transitioning to digital mediums and concepts in STEM, business, and social sciences [78, 107, 64] evolving to be more visually oriented, the educational landscape is seeing a surge in the use of visual-centric medias for information dissemination.

In an increasingly ocularcentric world, we find ourselves inundated with detailed graphics that inform our daily decisions. Charts that outline the complexities of a global pandemic shape our health choices, often dependent on visual perception, with minimal consideration for non-visual accessibility [58, 190] (ref fig 1.1). Moreover, visual maps depicting hurricane trajectories and wildfire areas steer our safety strategies [207, 43]. Furthermore, with the proliferation of educational games in schools, like Dreambox and Minecraft Education Toolkit [149, 101], there is an increased reliance on the visual modality for knowledge acquisition. The proficiency in accessing and accurately interpreting these visuals has burgeoned into a critical skill in our visually-driven society.

For individuals with blindness and other visual impairments (BVI), alternative methods are essential to access visual information. Digital graphics, such as images, graphs, and

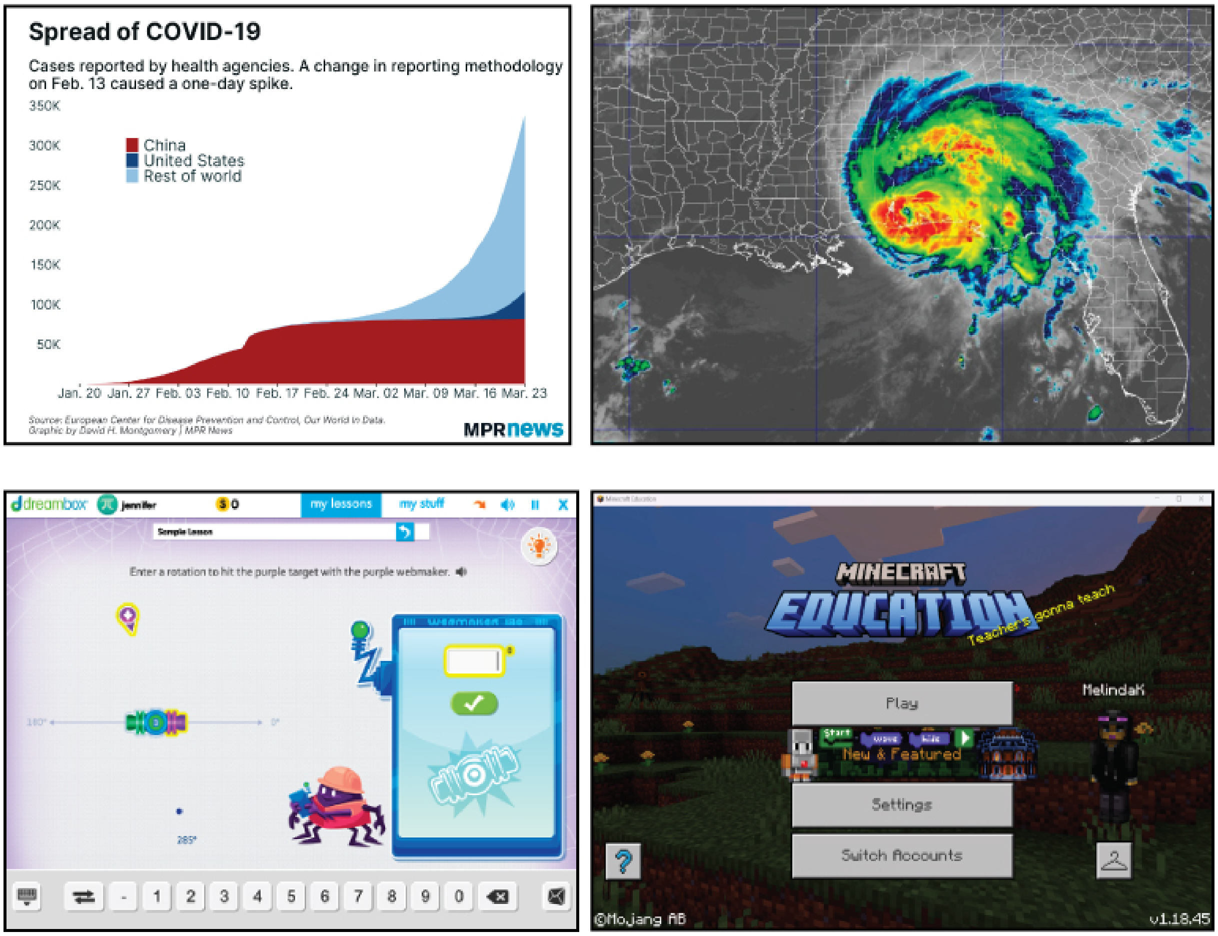

Figure 1.1: clockwise, starting from topright: a)COVID-19 chart from the website of MPR news [138], b)A 2020 hurricane map by PBS news for hurricane sally overlaid on the county map of south east US [157], c)Lobby of Minecraft's education suite used in several classrooms across US since 2016 [136], and d) An example question from Dreambox Learning's 6th grade suite teaching students how to use 180 degree numerals to determine angle to a given target on the interface [52]

animations, can be accessed through tools like alt-texts and audio-summaries, which are compatible with screen-readers [212, 89, 72]. In the tangible realm, tactile graphics (such as fig 1.2) play a pivotal role . These are designed with raised lines and textures to represent visual data, enabling users to "read" through touch. In my work, I adopt a colloquial definition of the term "read" that extends beyond its visual connotation to also include the act of perceiving information through touch, hearing, and varying degrees of vision. In education, tactile graphics are fundamental. They are widely used in numerous contexts, providing BVI students a vital means to interpret and interact with visual materials. Traditionally, in classroom settings, educators use verbal summaries or tactile graphics to promote inclusion

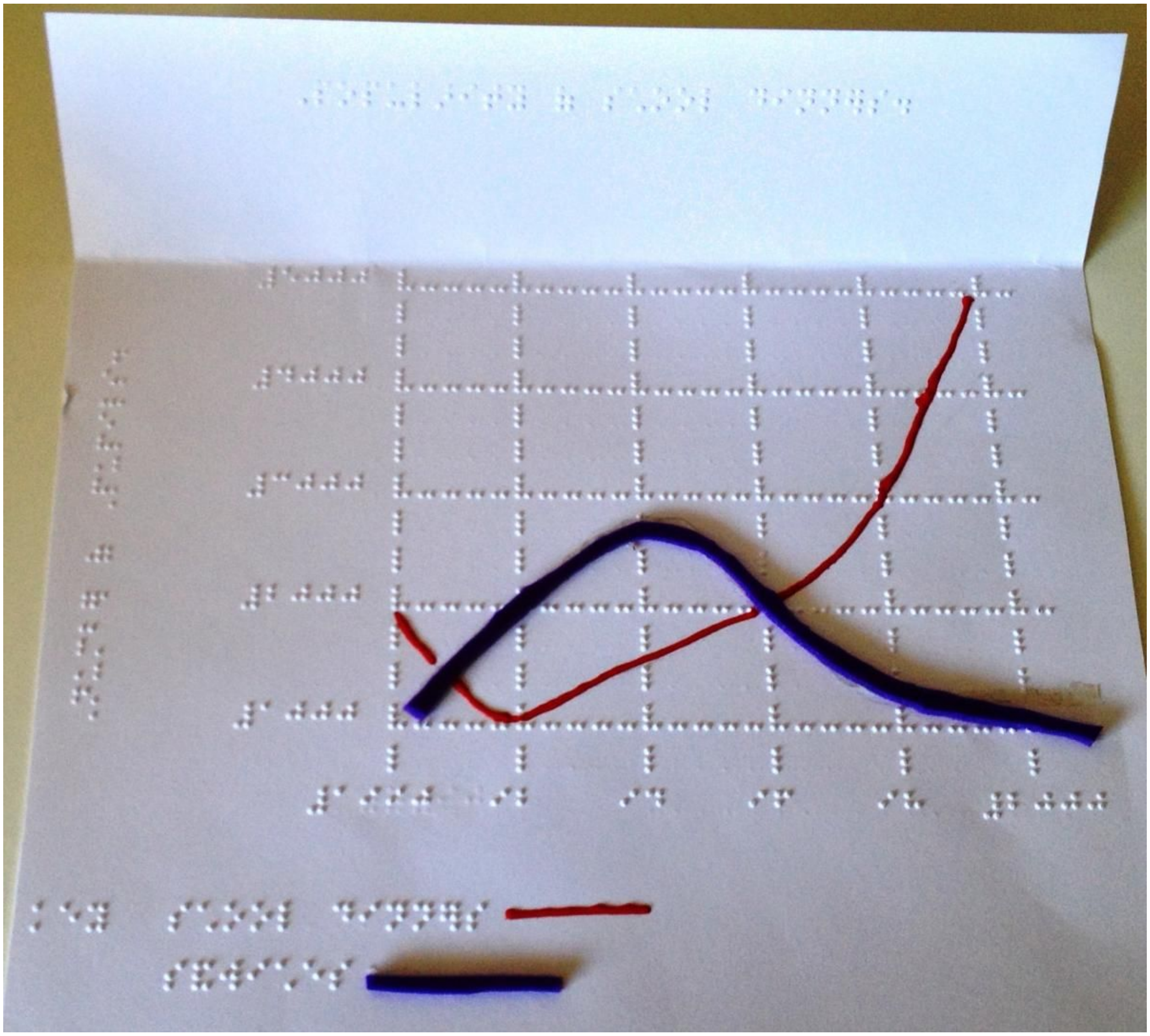

Figure 1.2: A Tactile Graphic created using Wikki Stix on a braille paper with grid lines. Braille markers were made using a Perkins braille machine [156]

when referencing graphical materials [179, 180].

In this dissertation, I explore audio-augmented tactile graphics as an innovative approach to present and interpret visual information in non-visual forms, in the context of educational environments. I refer to these multimodal representations, which integrate audio and tactile elements, as “audio-tactile graphics”. My hypothesis guiding this research is that audio-tactile graphics hold the potential to assist educators in achieving certain educational outcomes that tactile graphics might not fully address. Existing research highlights several advantages of audio-tactile graphics over traditional braille-labeled tactile graphics, especially in conveying intricate information effectively. Yet, their adoption beyond research contexts remains largely unexplored. My study positions audio-tactile graphics in the educational landscape, bringing together all stakeholders committed to promoting equitable access for BVI students. More specifically, I investigate the ramifications of integrating audio-tactile graphics into established teaching practices and determine their compatibility with the educational objectives crafted for BVI students by educators.

1.1 Research Questions

In this dissertation, I introduce three projects centered on understanding the subsequent exploratory questions related to the prolonged utilization of the audio-tactile graphics system in educational institutions. Research questions guiding these studies are:

- **Understanding the Context (RQ1)**: How does the workplace in which educators transcribe tactile graphics impact the transcription workflow and choice of transcription tools?
- **Situated in Current Practices (RQ2)**: How would educators collaborate in their current workplaces, using existing tools, to design audio-tactile graphics which meet their teaching requirements?
- **Simulating Use in Context and Current Practice (RQ3)**: How can audio-tactile graphics incorporate current design practices, instructional strategies, and contribute effectively towards teaching goals?

To address the first research question, I examined the prevailing processes of tactile graphic production and instruction in both schools and transcription agencies. For the second question, I conducted co-design workshops, wherein educators created audio-tactile graphics within their professional settings, using tools they were familiar with. To respond to the final question, I observed educators utilizing audio-tactile graphics in their teaching over a span of six weeks. This observation shed light on the potential applications of audio-tactile graphics in classrooms, the innovative pedagogies this technology can foster, and its capacity to encourage autonomous learning among BVI students.

1.2 Statement of Thesis

There are three primary stakeholders who play pivotal roles in influencing the design and sustained utilization of audio-tactile graphics systems within educational institutions- educators of visually impaired students, classroom teachers,

and the end users (i.e., BVI students). Consequently, the design of the audio-tactile graphics system should be thoughtfully tailored to acknowledge the needs of all the stakeholders involved and the workflows which facilitate its integration in school settings. From a comprehensive viewpoint, audio-tactile graphics systems emerge not just as tools that improve image access for BVI students, but also as a catalysts for exploring innovative pedagogies and aiding educators in achieving specific educational milestones.

Earlier research on audio-tactile graphics primarily focused on assessing device usability, resulting in foundational design guidelines and interactions for robust audio-tactile graphics. My research expands on this foundation. Designing a new assistive technology is not just about meeting the needs of the end users. Recognizing the interplay between stakeholders, systems, and situational dynamics offers a more nuanced perspective about the pedagogies, educational tasks and classroom environment that are enabled through the use of such assistive technologies. Education is but one facet of several contexts in which audio-tactile graphics can be utilized. Through my research, I demonstrate the value that audio-tactile graphics bring to the broader education ecosystem such as - their ability to encourage inclusive teaching practices in mixed-ability settings, cultivate autonomy among beginner tactile graphic readers, and enable educators to customize graphics based on tasks and lesson plans for repeated use. The design guidelines I propose based on the results of the three studies are grounded in the practice of transcribing tactile graphics in educational contexts. I build upon the traditional process used for tactile graphic production in the way I have organized the guidelines. The first step in these guidelines (Sec 5.7.1) aligns with the traditional process, with the exception of adding braille labels, as our approach incorporates audio-labels instead.

In the subsequent step (Sec 5.7.2), we have streamlined the process of co-locating audio-labels and tactile elements. This includes considerations for the sizing, buffer spacing between tactile and interaction zones, and recommendations for distinct tactile symbols that have been utilized to indicate the presence of an audio-label in all the graphics used in my studies. This particular step in the guidelines represents a novel contribution, developed through iterative design processes carried out during studies 2 and 3.

The final step (Sec 5.7.3) in the guidelines offers recommendations for effectively distributing information within the hierarchical structures of audio-labels. These recommendations aim to enhance tactile exploration by complementing it with meaningful audio cues. In this stage, we have referred to established audio-tactile graphics design guidelines from previous lab-based research in HCI, validating their applicability in educational contexts. Our validation process assessed these guidelines against key learning outcomes, including support for independent exploration, improved reading and exploration speeds, and compatibility with typical educator workflow of modifying a graphic to be reused for alternate educational tasks such as quizzes, homework, or in-depth study.

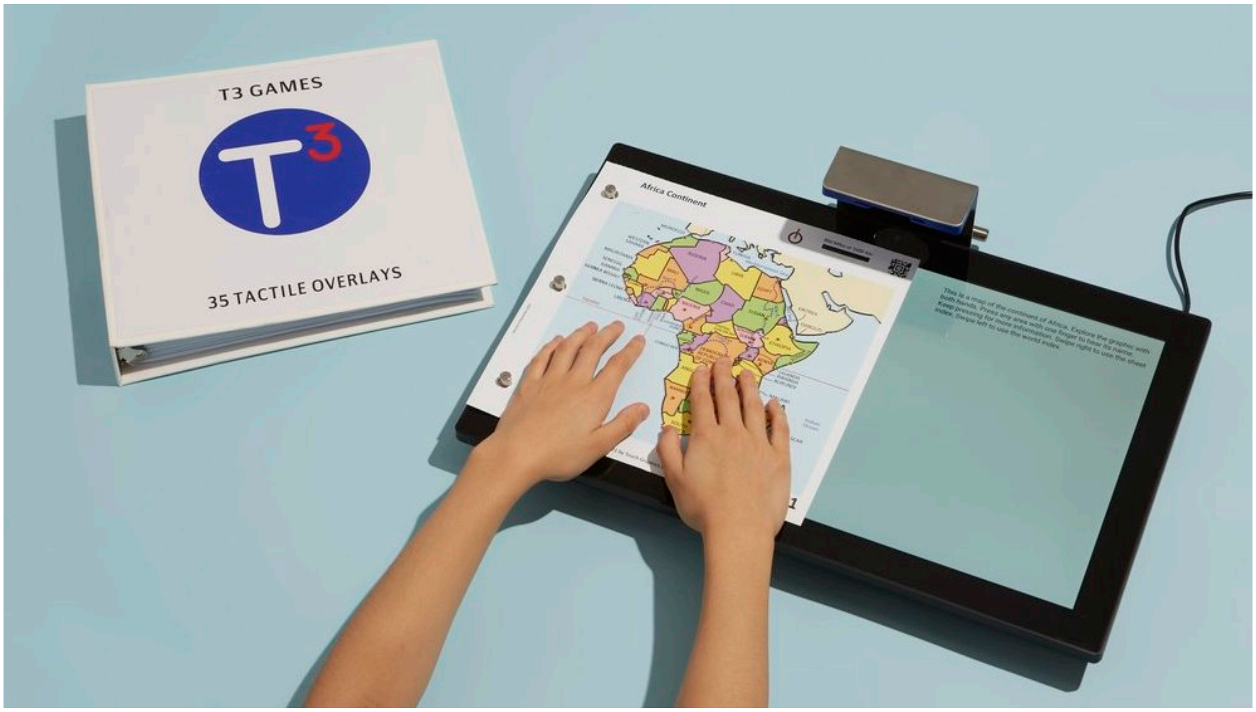

Figure 1.3: T3 Tablet by Touch Graphics [206] consist of the tablet, the tactile overlay sheet and a database of the audio-labels corresponding to the overlay sheet that is automatically downloaded by the tablet when one places the sheet on it.

In my studies I used the T3 audio-tactile tablet [206] (Fig. 1.3) for creating and presenting audio-tactile graphics. The T3 is a modified version of the TMAP audio-tactile tablet. The TMAP device was developed in partnership with BVI readers, Teachers of Students with Visual Impairments (TVI)s, and access technology specialists, and underwent a rigorous evaluation with BVI readers [135]. The T3 tablet comprises a tactile graphic overlaid on an Android tablet. The tactile overlay presents a part of the graphic in the form of tactile lines and patterns. The Android tablet announces textual details from the graphic that are associated to the tactile elements on the overlay. Users can interact with the T3 tablet through gestures that do not hinder the exploration of the tactile diagram. Specifically, the T3 tablet supports one-finger swipe gestures, similar to talkback screen reader interactions, to navigate menus for adjusting volume, speech rate, and accessing tutorials. Users can query for audio-labels by pressing down on the tactile element in the overlay. Upon placing the overlay sheet on the screen, the tablet automatically loads an audio-label file associated with the overlay. One can compare the exploration procedures involved in reading a T3 graphic to a combination of the hand movements required to read tactile graphics and the gestures executed on tablets or mobiles utilizing a screen reader. Additionally, T3 graphics can embed audio-labels in a hierarchical manner, with deeper labels being accessible by pressing upon the same location multiple times.

1.3 Dissertation Outline

The chapters of this dissertation are laid out as follows:

- In **Chapter 2**, I delve into existing literature on tactile and audio-tactile graphics, examining the infrastructure that bolsters inclusive education practices in public schools across North America. I also assess previous studies centered on the introduction and integration of assistive technologies within educational frameworks. This literature review highlights notable gaps in our knowledge, particularly in the inclusion of perspectives from both BVI students and educators during the development and application of audio-tactile systems for educational use.

- **Chapter 3** delves into a study undertaken to scrutinize the prevalent procedures of tactile graphic production and instruction in schools and transcription agencies. The results highlighted that professionals involved often take additional measures beyond merely crafting the graphics, as a default part of their roles within schools or transcription agencies. Observing transcription within its actual workplace setting illuminated how factors, such as collaborations with classroom teachers and clients, organizational structures, and direct interaction with end-users, play pivotal roles in design choices and the entire transcription process. We acknowledge these contextual factors in our method for integrating the T3 and its transcription workflow, as we proceed to examine a co-design workshop with educators in the subsequent study.

- **Chapter 4** details a co-design workshop aimed at gauging how educators might conceptualize audio-tactile graphics for the T3 tablet within their familiar work environment, leveraging tools they routinely use. This study offered preliminary insights into how participating educators would approach audio-tactile graphic design, drawing upon their existing expertise in tactile graphics and other assistive technologies. One notable takeaway was the potential of detailed audio-labels on the T3 to enhance exploration and, consequently, autonomy among BVI students. This anticipated benefit associated with audio-tactile graphics on was evaluated along with other education goals educators had for the T3.

- In **Chapter 5**, I cover the field deployment study where educators were equipped with T3 tablets. Observations were made on their utilization of audio-tactile graphics in teaching over a six-week duration. This exploration presented a feasible approach to employing the T3 in academic and O&M exercises. Throughout the deployment phase, we discerned various tasks and educational goals of TVIs that the T3 adeptly supported, along with areas where it encountered challenges.
- In **Chapter 6**, I provide a comprehensive summary of this dissertation, weaving my contributions with the progress observed in the domain of HCI, accessibility, and education-technology. Additionally, I highlight potential avenues for future endeavors, building upon the groundwork established in my research.

CHAPTER 2

Background and Motivation

Tactile graphics convey non-textual information, such as STEM diagrams, illustrations, charts, and drawings. Wright argues that the primary objective of these graphics is to communicate the underlying concept or information of a visual graphic, rather than merely creating a tactile equivalent of the visual representation [216]. Tactile acuity, defined as the ability to discern closely spaced points or patterns by touch, varies among BVI individuals. This variation is influenced by several factors, including the age at which vision was lost [169], the force of contact between the surface and skin, and gender [73]. Beyond possessing keen tactile acuity, receiving training in tactile graphic interpretation and frequent exposure to such graphics are essential for achieving fluency in reading them [25].

Educating BVI students in the interpretation of tactile graphics is an integral component of the extended core curriculum in the United States [175].

BVI students often face a considerable delay in developing tactile graphics literacy compared to their sighted peers. This is primarily because tactile graphics literacy requires consistent interaction with complex and detailed graphics showcasing a variety of patterns – a type of exposure that is naturally integrated into the daily lives of sighted individuals through visual means. However, for BVI students, this exposure is not as readily available or integrated into their everyday environments.

The deficiency in early exposure and practice becomes evident in foundational classes, where BVI students often require a support and guidance from special-ed instructors, especially in tasks centered around the interpretation of tactile images. This is a stark contrast to their sighted counterparts, who, due to their constant interaction with visual graphics, have a more developed skill set in image interpretation from a younger age. [218]

Addressing this gap is crucial for leveling the playing field and ensuring that BVI students receive the support and resources they need to develop tactile graphics literacy at a pace comparable to their sighted peers. This entails a deliberate effort to integrate tactile graphics into their learning environments and daily activities, fostering a learning experience that is both inclusive and empowering.

A study by Zebehazy and Winton surveying educators of the visually impaired (N=306) disclosed a concerning statistic: only about 20% teachers believed their students could independently handle mathematical graphics [217]. Rosenblum argues that tactile graphics literacy goes beyond acquiring tactile acuity; it is the skill to effectively and precisely identify and utilize information for task completion [171].

The learning process for tactile graphics is progressive: BVI students initially discern the specifics of each component in sequence, subsequently integrating these fragments by grasping the spatial interrelations among various elements. Prior research emphasizes the importance of early and consistent exposure to tactile graphics, which is vital for students to formulate an effective, personalized exploration methodology [217, 40].

TVIs have a number of instructional strategies at their disposal to coach students in honing their exploration techniques. These methodologies are intricately designed, taking into account the subtle complexities in the differences between tactile and visual perception [84]. Despite conveying analogous information, tactile and visual graphics are not identical in form and layout, a discrepancy attributed to the fundamental differences between tactile and visual perception.

2.1 Perception of tactile, audio and visual information

Visual perception operates on an "overview-first" principle, wherein the broader picture is assimilated before delving into intricate details [84]. The realm of information harnesses this characteristic of vision to represent data in a manner more insightful as a comprehensive visual than as discrete figures. Schneiderman's Visual Information Seeking Mantra highlights this perceptual strength by asserting, *"the bandwidth of information presentation is potentially higher in the visual domain than for media reaching any of the other senses"*. Accordingly, the paradigm of *"Overview first, zoom and filter, then detail on demand"* is aptly suited for visual perception [186]. Visual perception naturally gravitates towards gaining a holistic understanding of an image before pinpointing specific details, guiding subsequent exploratory actions based on this comprehensive grasp.

Tactile perception operates more sequentially than visual perception. In tactile sensing, components of an image are perceived one after another, leading to the eventual understanding of the image as a whole [137]. Because touch senses stimuli that are physically close, tactile learners rely heavily on spatial cues near their bodies, known as the **egocentric frame of reference**. This sequential, egocentric processing leads to understanding spatial relationships step-by-step, with object locations perceived in relation to one's body. For individuals with visual impairments, processing complex **allocentric information** communicated through visually-oriented language—directions like *"left"* or *"right"*, distances such as *"near"* or *"far"*, and positions like *"next to"* or *"between"*—requires a solid grasp of tactile graphics. Adjustments in rotation, zoom levels, or shifts to different sections of an image may demand recalibration with the initial spatial orientation [129].

Pasqualotto et al found that their visually impaired participants preferred an egocentric frame of reference during navigation exercises [154]. While they concluded that a visual frame of reference is crucial for developing an allocentric perspective, Giudice argues that constructing a spatial model for allocentric tasks is amodal, i.e - not specifically reliant on visual or tactile perception [71]. This indicates that individuals with visual impairments can successfully perform allocentric tasks if they can form a spatial mental model, a skill often developed through frequent exposure to tactile graphics. Incorporating audio with tactile learning can further support the construction of this spatial model required to perform allocentric tasks, since doing so is not contingent on a specific modality. Furthermore, since auditory information is typically associated with the world outside the body, combining audio and tactile sensations can help position tactile experiences within a reference frame that is not centered on the body. Audio-tactile interfaces have proven beneficial in previous studies, providing immediate feedback, adding layers of detail, facilitating information queries, and reducing tactile clutter [133, 79, 211, 148]. Additionally, combining audio with tactile modalities allows for information transmission over a broader bandwidth compared to using tactile methods alone [120, 34].

In conclusion, audio-supported tactile graphics assist in building a comprehensive spatial understanding, enhancing overall comprehension and task performance in areas currently served by tactile graphics alone. While existing research on audio-tactile interfaces often focuses on laboratory use from the readers' viewpoint [148, 88, 33, 133], my thesis investigates educators' perspectives. Specifically, I examine how these professionals might utilize audio-tactile graphics in educational environments and how such tools help them achieve their educational objectives.

This investigation is rooted in the contemporary practices educators employ when creating tactile graphics in academic settings. To understand path for future adoption of audio-tactile graphics, I consider the current infrastructure and ecosystem of tactile graphic production. The next section delves deeper into the methods educators currently use to produce tactile graphics.

2.2 Educators of Students with Visual Impairments

In educational settings, tactile graphics are essential, providing students with equal opportunities to engage with graphical content across various subjects. Disciplines such as mathematics and science frequently depend on visual representations to help students gather, analyze, and comprehend intricate data. Tactile versions offer BVI students the means to interpret this information through touch, paralleling the way their sighted classmates utilize visual resources.

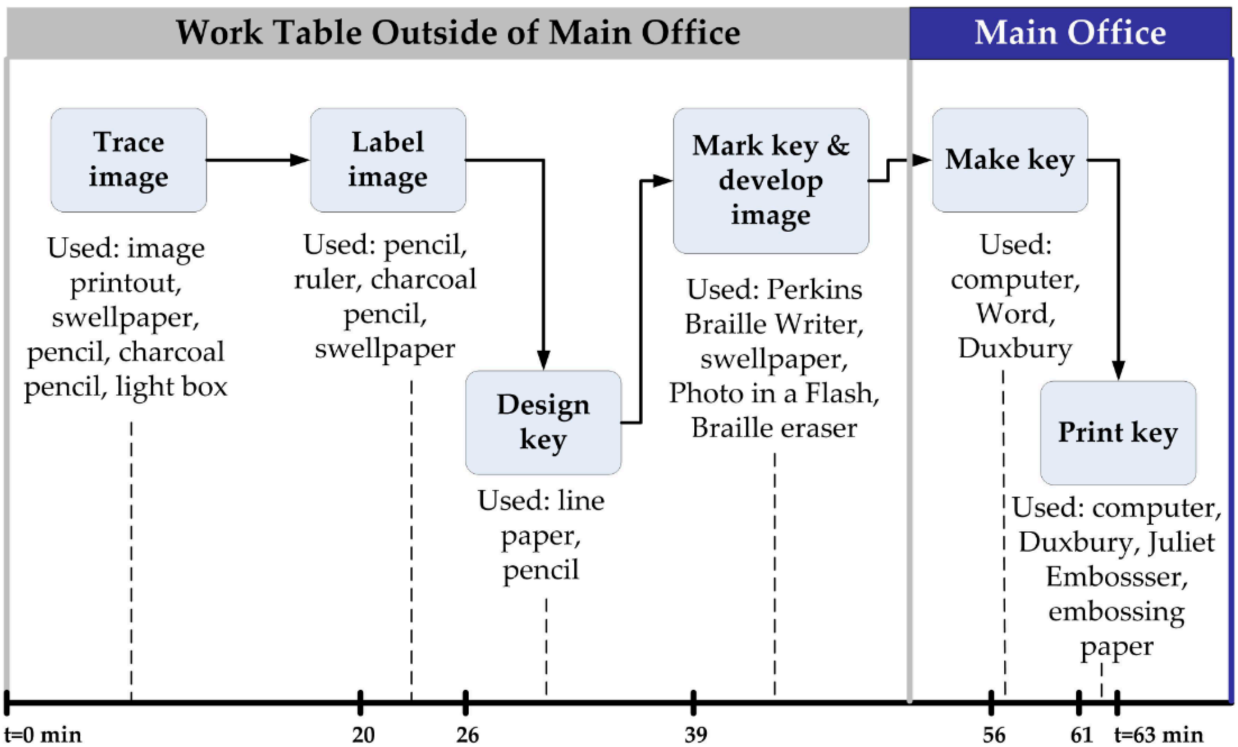

Figure 2.1: Ladner et al's Translation Task Flow which describes the steps required to transcribe a visual graphic into tactile graphic [111]

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The creation of tactile graphics, known as *"transcription"*, adapts visual source images to cater to the tactile understanding of students with visual impairments [92]. Prior studies have explored tools that enhance the efficiency of the tactile graphic transcription workflow [111]. Ladner and colleagues have outlined six primary steps in tactile graphics production: *tracing the image, labeling the image, designing a key, marking the key while developing the image, creating the key, and finally, printing the key.* This sequence is termed the Translation Task Flow (TTF) and visualized in figure 2.1. While the intricate and iterative nature of the process makes it challenging to link these steps directly to specific job roles, prior surveys allow us to distinguish five distinct roles of professionals in the tactile graphic transcription realm [111, 161, 196, 38, 192]. Throughout this dissertation, I will address these professionals as educators, including the following roles:

- **Teachers of students with visual impairments**: TVIs are specialized educators whose main goal is to tailor educational content and practices to meet the needs of students experiencing visual impairments. TVIs pivotal in the process of making information accessible and comprehensible for these students, often concentrating on adaptations like large print, braille, and tactile graphics. In today's educational landscape, with technology and multimedia becoming ever more integral, TVIs need a thorough understanding of digital accessibility issues. They are also expected to collaborate with individuals in tech and design to ensure digital content is universally accessible. Among TVIs, there are specialists dedicated to aiding individuals with visual impairments in comprehending and navigating their physical surroundings; these experts are referred to as Orientation and Mobility (O&M) specialists. Their job is to coach students in skills such as map reading, environmental interpretation, and the use of assistive navigation technologies. Given the constant evolution of our physical spaces, both indoors and out, O&M specialists serve as a crucial link between visually impaired individuals and their surroundings, ensuring these students can navigate effectively and advocate for themselves in various environments.

- **Braille Transcribers and Tactile Graphic Artists**: Braille transcribers are individuals trained in converting printed text into braille. They play an essential role in making written materials, such as books, manuals, and other printed documents, accessible to people who are blind or visually impaired. Braille transcribers use software such as Duxbury Braille to create digital braille documents of the print versions that are printed using braille embossers. Tactile graphic artists, sometimes simply referred to as tactile graphic designers, specialize in designing tactile diagrams, maps, illustrations, and other visual representations for educational materials, informational brochures, and more so that they can be interpreted by touch. The aim is to ensure that complex visual references used in coursework, whether this is the layout of a building or a chart showing statistical data, can be accessed and comprehended by BVI students using their sense of touch to access information. Tactile graphics represent a meticulous selection and representation of information through tactile patterns, rather than a straightforward transposition of every detail encoded in the original visual source material. (for instance, figure 2.2)

  According to Siu et al [192] tactile graphic artists are transforming into alternative

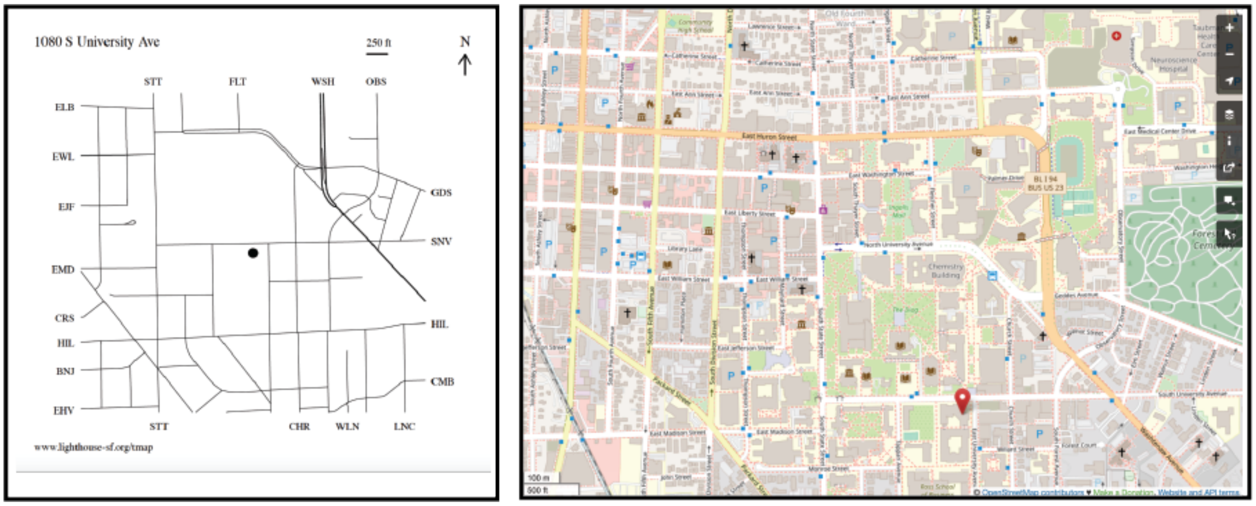

Figure 2.2: Map of 1080 S University Ave, Ann Arbor, MI on TMAP [1] (left) and on the Open Street Map website (left). Notice the level of simplification performed to derive the TMAP version of the map that is aimed to serve specific purpose instead

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media specialists. In the era of digital information, transcribers not only provide braille but also ensure digital content is accessible. They need to understand the accessibility of various digital formats and how the content they create interacts with different user technologies. Braille transcribers and tactile graphic artists harness various image-editing tools, including mainstream software like Duxburry [54], Microsoft Word, Adobe Illustrator and CorelDRAW [155], as well as specialized applications such as BrlGraphEditor [19, 20], TGD Pro (Tactile Graphics Designer Pro) [2], and Tiger Designer [208]. Their primary objective is to create digital image masters of tactile graphics that are carefully designed ensuring its suitability for tactile interpretation. Tools such as Tiger Tactile Graphic Designer [208] also allows the modification of pre-existing digital image file and facilitates adding Braille text within the image. When it comes to tactile reproduction of these digital files, the most common methods include the use of swell paper, embossing, and thermoforming [111].

- **Proofreaders**: Proofreaders are specialized professionals who ensure the accuracy, clarity, and usability of tactile graphics and braille transcriptions. Their role is critical in the production process of educational and informational materials for BVI readers. A subsection of transcribers sometimes also proofreader their own work before it is sent out for print. Proofreaders, like braille transcribers and tactile graphic artists are trained and certified through organizations dedicated to ensuring they follow established standards for accuracy and readability. Such organizations include the National Library service for blind and Print Disabled (NLS), National Braille Association (NBA), Canadian Braille Authority (CBA). Additionally several university programs offer training programs for tactile graphic artists and TVIs that cover proofreading basics [205].

- **Access technology specialists**: Access technology specialists are professionals who possess expertise in the use of assistive technologies. These specialists have a deep understanding of making education accessible for students with disabilities and how technology can be leveraged to mitigate challenges faced by students with disabilities. Their roles typically include assessing specific needs of individual students, training them to use a tool or software they determine to be of help to the student, advocating to other educators and parents to provide their student an inclusive learning environment.

- **Para-educators**: Paraeducators, also known as paraprofessionals, teacher's aides, or instructional assistants (IAs), serve as vital support staff in educational environments, working closely with certified or licensed educators. Their role becomes particularly specialized when assisting students with visual impairments, as they ensure these students can effectively access the general education curriculum and actively engage in all school activities. While TVIs focus on specialized instruction, paraeducators often spend more one-on-one time with students, providing immediate assistance during classroom lessons and activities. Their responsibilities include a range of tasks, from adapting materials and assisting with mobility to facilitating social interactions. Additionally, they play a key role in monitoring student progress to provide feedback to the TVI and other educators involved in a student's education plan and acting as a communication bridge between classroom teachers, TVIs, and tactile artists to guarantee that the academic needs of the students are continuously addressed. Paraeducators do not replace the expertise provided by TVIs or O&M specialists. Instead, they work as part of a collaborative team to ensure that students with visual impairments receive a comprehensive and inclusive education.

It is essential to understand that the roles described are specific to the US education system, especially within the framework of the Expanded Core Curriculum (ECC) tailored for visually impaired students. My dissertation centers on participatory research with educators who might assume one or several of these roles in classrooms. Through their insights, I aim to delve deeper into context-specific feedback on how tools like the T3 can be seamlessly integrated into the existing infrastructure designed for making graphics accessible to visually impaired students. It is not just the integrity and dependability of the assistive technologies that matter, but equally crucial is the team of educators committed to crafting an inclusive educational experience that incorporates these technologies. My research is embedded within the collaborative workflow that binds these educators together within a student's support team.

2.3 Engaging Educators In Research.

In a preliminary study, I compared the strategies that BVI users utilized when solving crosswords via an audio-tactile interface with another interface that used an NVDIA screen reader [168] (ref fig 2.3). All participants indicated a lack of prior experience with audio-tactile graphics, necessitating a dedicated portion of the study session to training on the audio-tactile interface.

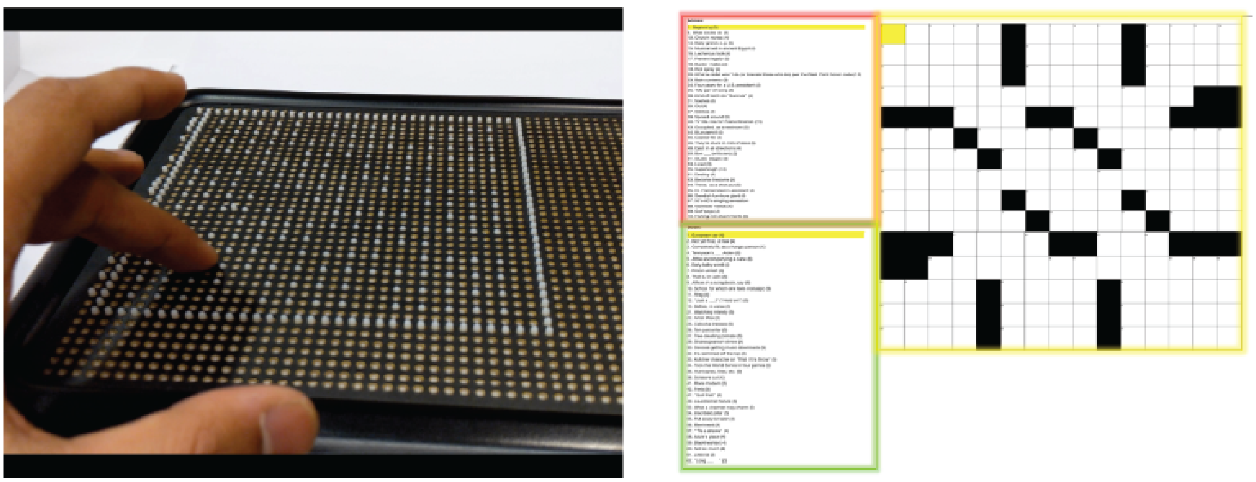

Figure 2.3: Photos of the two crossword puzzle interfaces that participants used to solve crossword puzzle in [168]: (left) The audio-tactile crossword interface on a full-page refreshable braille display - graphiti, and (right) a snippet of the APH's screen-reader compatible crossword puzzle website.

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Given the significant disparity in participants' experience with screen readers and with audio-tactile graphics, this earlier study was designed to compare their problem-solving strategies for the two crossword puzzle interfaces, rather than relying on direct performance indicators like the time taken for completion or the number of words solved.

Comparing performance on interfaces where user familiarity varies significantly could yield biased outcomes. Training before the studies would not yield the same outcome because as highlighted in the preceding section, tactile graphics literacy is cultivated through prolonged and consistent interaction with tactile graphics.

Thus, in the research presented in this dissertation (Chapters 3, 4, and 5), I center my attention on educational environments where BVI students hone their skills in interpreting audio-tactile graphics. My approach builds upon existing educational workflows that train BVI students to use an array of assistive technologies, such as tactile graphics, screen readers and refreshable braille displays. The overarching aim is to leverage these pre-established educational frameworks to seamlessly introduce and integrate the use of audio-tactile graphics on the T3 in classrooms and enabling educators to effectively utilize the T3 as part of their instruction toolkit. Existing research supports the notion that blind students are more inclined to adopt assistive technologies long-term when these tools are integrated into their learning process from an early stage [113, 81]. Focusing on an educational setting can therefore inform long-term adoption of devices such as the T3.

Despite the relatively recent advent of audio-tactile graphics, I argue that we have now reached a point where it is crucial to shift our focus toward studying how audio-tactile graphics can aid students and educators in current educational ecosystems. An initial body of research focuses on crafting functional and user-friendly graphics tailored to the needs of BVI users, establishing a fundamental understanding of how to incorporate these tools to perform day-to-day tasks [201, 65, 135, 124, 200, 182]. Building on this work, a more recent phase of research on audio-tactile graphics is focused on understanding how these technologies reshape existing educational workflows, tasks, and processes [133]. My thesis situates itself in this later phase of research, investigating the influence of audio-tactile graphics in educational scenarios.

Integrating audio-tactile graphics into educational contexts can profoundly influence existing educational workflows, instructional methods, and eventual student outcomes. Historically, research in audio-tactile graphics has been predominantly driven by user experience, culminating in the development of design guidelines aimed at amplifying the efficiency and user-friendliness of tools tailored for BVI individuals. Among the most significant advancements are:

- Design guidelines for communicating spatial layouts such as of web-pages and interactions for manipulating them as per user's commands [116].
- The creation of hands-free interfaces equipped with voice command capabilities for enhanced interaction [65].
- Techniques devised to minimize tactile congestion by forgoing the necessity for braille labels, yet ensuring the conveyance of abundant textual data [148, 88, 188, 210, 76].
- Strategies to streamline tactile exploration by utilizing succinct language in audio labels and offering adaptability via the simultaneous use of both braille and audio

labels [148, 76].

Despite these advancements in the development of audio-tactile graphics as a medium, there is a notable deficiency in research which looks at the perspectives of educators and other essential stakeholders who would be producing audio-tactile graphics or teaching BVI students using audio-tactile graphics. Engaging stakeholders in the design process is a common and widely recognized methodology in previous studies involving the development of an assistive technology [4, 5, 46, 90]. In my research, I adopt a participatory methodology, recognizing that educators possess extensive knowledge about the use of audio and tactile assistive technologies, an awareness of environmental limitations, and other vital considerations pertinent to educational settings.

Aflatoony et al. highlight the significant role of stakeholders such as occupational therapists (OTs) in early stages of assistive technology development, stating that "OTs champion principles of client-centered intervention and utilize their comprehensive training across biomechanical, neurological, environmental, and psychosocial domains to devise customized solutions" which foster independence among people with disabilities and improve participation within society [4]. The Person-Environment-Occupation (PEO) framework, frequently referenced in occupational therapy literature, encapsulates this holistic approach [197, 114]. The individual components that make up the PEO together provide a comprehensive model of actors affecting the assistive technology:

- **Person**: This refers to the individual, including their skills, abilities, experiences, and attributes. It encompasses physical, cognitive, emotional, and social aspects of the person.
- **Environment**: This includes the physical, social, cultural, and institutional surroundings in which the person lives and conducts their activities. The environment can either facilitate or create barriers to participation.
- **Occupation**: This represents the activities and tasks that the person engages in on a daily basis. Occupations give meaning and purpose to life and can include work, leisure, self-care, and social participation.

Through a comprehensive series of studies culminating in an in-class deployment of the T3 audio-tactile system (environment), my research provides grounded insights based on the unique experiences of participating educators and their students (person), while facilitating a variety of daily tasks typically accomplished using alternative methods for accessing graphics (occupation). The observations and insights from my dissertation research provide the contextual framing required to understand how personal, environmental, and occupational factors collectively influence the design and integration of audio-tactile graphics within educational settings. In Chapter 6, I revisit the PEO framework to delve into and analyze the intricate interplay between the T3 system and other assistive technologies utilized in schools, examining how they collectively improve a students' access to educational content.

2.4 Studies on Adoption of Assistive Technologies in Education

The objective of assistive technology developers should include facilitating a sustained use of the technology by blind users and other stakeholders. Assistive technology plays a pivotal role in educational inclusion, bridging gaps and cultivating an environment conducive to learning for all. However, its long-term effectiveness depends greatly on its continuous integration into teaching practices and educational infrastructure [160]. Considering long-term adoption allows educators, administrators, and technology designers to gather critical insights about the performance of these technologies in authentic academic settings, and their seamless incorporation into a variety of educational programs and activities. Past research examining the determinants of long-term assistive technology adoption in education has highlighted key factors such as:

- **Educator Knowledge about the Technology**: limited staff knowledge and awareness about the assistive technology was a significant barrier to its use in classrooms [81, 178]. A recent survey asking a sample of educators of students with disabilities in Michigan revealed that nearly 70% reported limited knowledge about the assistive technology being a barrier for them due to reasons such as lack of training. [145]

- **Needs Assessment and Satisfaction**: If one fails to accurately identify and address the user's needs when building an Individualized Education Plan (IEP), dissatisfaction and eventual abandonment of the technology are likely outcomes [44, 226].

- **Placement exams**: Part of developing an IEP is to conduct thorough assessments of students' visual acuity, visual field, functional use of vision, and to determine their tactile and auditory media preferences. These evaluations contribute to effective planning for deciding which assistive technology is right for a student, and which associated services, school accommodations, and curriculum modifications, will ultimately enhance the likelihood of student satisfaction and success [204, 91, 59, 63].

While recognizing the systemic barriers to technology adoption in accessible education, it is important to highlight the specific challenges posed by limited time and support available to TVIs and other special education professionals, who are often responsible for large groups of students spread across multiple schools [179, 16]. Funding constraints [145, 81, 146], a lack of political motivation or visionary leadership [145], and scarcity of TVIs to meet the demand [153] are acknowledged as major barriers to the adoption of access technology. My research primarily centers around factors that emerge in the context of a classroom and influence the long-term adoption of an assistive technology.

Kintsch and DePaula present a comprehensive framework for the adoption of assistive technologies, grounded in empirical research and observational data [99]. While initially conceived for the integration of assistive technologies into the daily lives of individuals with disabilities, this framework—referred to as the Kintsch and DePaula framework—also holds relevance and applicability within educational settings (ref fig2.4).

Understanding assistive technology through the Kintsch and DePaula framework offers valuable insights for designers and educators, aiming to mitigate the risk of technology abandonment by pinpointing critical factors that impact each step of the process. Consisting of four steps—development, selection, learning, and integration—this framework provides a structured approach to understanding the sustained utilization of assistive technologies:

- **Development**: During the development phase, one of the primary challenges lies in catering to a diverse range of disabilities, spanning from moderate to severe conditions [42, 150]. Researchers advocate for a user-centered approach during development stage of new assistive technologies, emphasizing the need for systematic usability evaluations [42, 158, 162]. As previously highlighted, significant advancements in audio-tactile graphics systems have covered user-centered usability evaluations of novel audio-tactile interfaces and can be recognized as part of this development stage.

- **Selection**: Kintsch and DePaula assert that the selection of assistive technologies transpires within the social milieu of its usage. In this stage, users, along with various stakeholders such as family, classmates, and educators, discern and choose assistive technologies that best align with their needs. A comprehensive assistive technology skill assessment, conducted by a assistive technology specialists, can significantly aid individuals with disabilities in identifying the most suitable tools for their requirements [67]. Such an assessment can garner valuable insights from existing assistive technology usage patterns, user interests, and capabilities [87]. Currently, there exists a knowledge gap concerning the specific contexts and tasks wherein educators and students would opt for audio-tactile graphics over other available assistive technologies. There is also a deficiency in the precise understanding of the prerequisite skills necessary for students to effectively utilize audio-tactile graphics. We document our findings on the essential

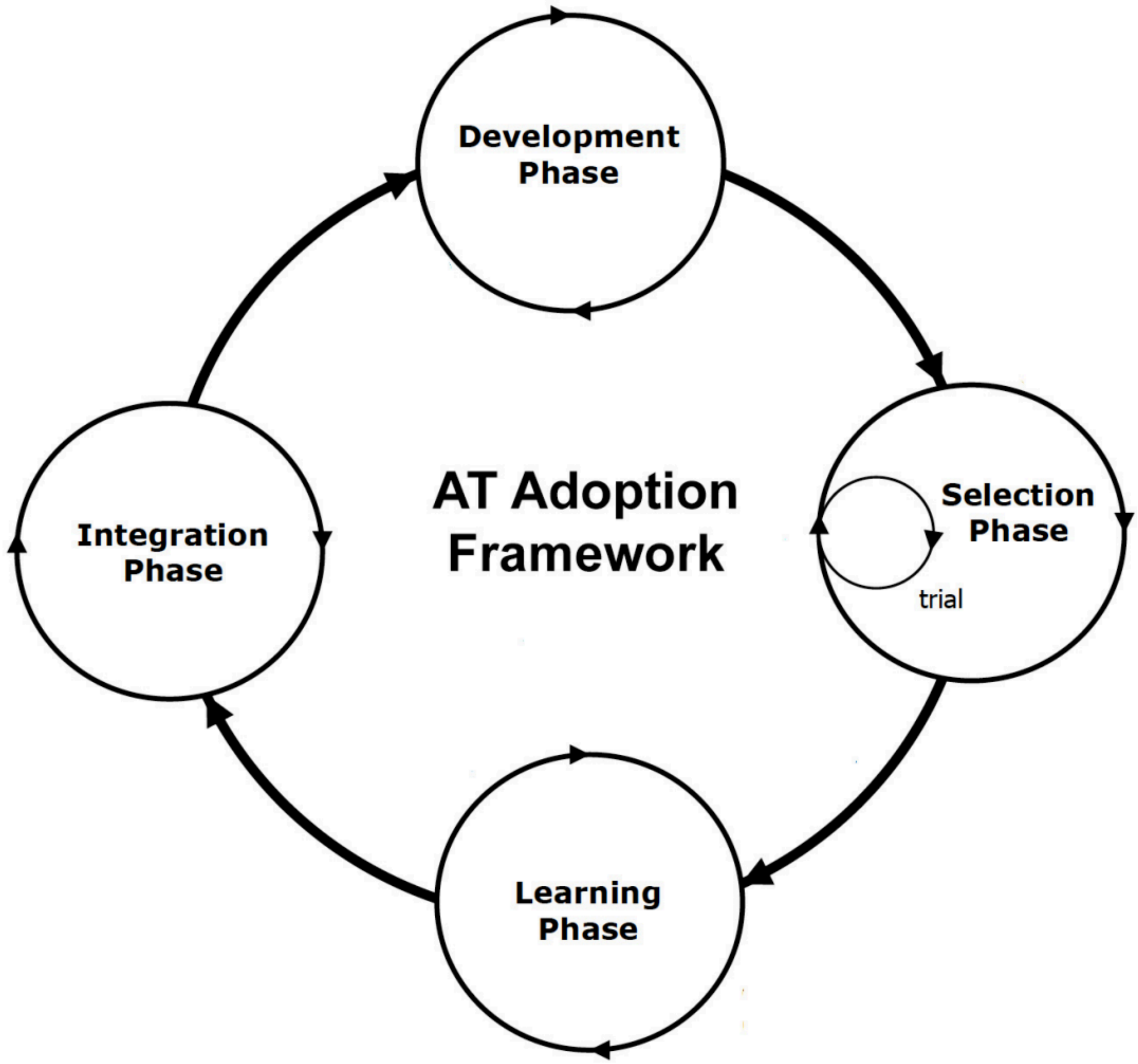

Figure 2.4: The Kintsch and DePaula framework for assistive technology adoption [99]

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preconditions for students to adeptly engage with audio-tactile interfaces as part of the insights from our third study.

- **Learning**: In this phase, users acquire the necessary skills to operate assistive technology effectively. Kintsch and DePaula emphasize the importance of educators being proficient in using the technology, possessing the capability to impart these skills to their students. They conceptualize the learning of assistive technology as an ongoing process, crucial for sustained utilization beyond educational settings. For example, students utilizing screen readers must adapt to new versions and features following software updates [12]. This necessitates a continuous learning and skill-upgradation process, which may at times be undertaken independently by people with disabilities. The current lack of a comprehensive audio-tactile system impedes our understanding of how educators can subsequently instruct their students to access academic materials, troubleshoot issues autonomously, and transition to more intricate audio-tactile graphics systems.

- **Integration**: Kintsch and DePaula characterize integration phase as the incorporation of a new device into routine activities, aspiring for user proficiency in its utilization. In educational settings, this translates to the assimilation of assistive technology to an extent where it becomes an integral component of the instructional and learning activities engaged in by a student. Such integration of technology within a learning environment, particularly in educational technology, is commonly analyzed through the Technological Pedagogical Content Knowledge (TPACK) framework. This approach provides a comprehensive understanding of how technology interacts with pedagogy and content, facilitating a seamless educational experience.

The Technological Pedagogical and Content Knowledge (TPACK)framework was developed to describe what teachers need to know to effectively implement technology into their teaching practices [103]. In the space of education-technology research, TPACK is regarded as a robust framework to breakdown the pre-requesits and measure the integration of a technology in education [53, 176, 106]. This framework helps identify identifies three types of knowledge instructors need to combine for successful technological integration—technological, pedagogical, and content knowledge.

TPACK consists of three domains of knowledge that collectively impact the use of a technology in the classroom:

- **Technological Knowledge (TK)** is knowledge about various technologies, both assistive and instruction, and how they can be used in educational settings in various contexts.

- **Pedagogical Knowledge (PK)** is about the methods and processes used for teaching, or the "how" of teaching. This involves understanding how students learn, classroom management, lesson planning, and student assessment.

- **Content Knowledge (CK)** refers to the subject matter that is to be learned or taught, essentially the "what" of teaching. Teachers must have deep knowledge of the content they are teaching.

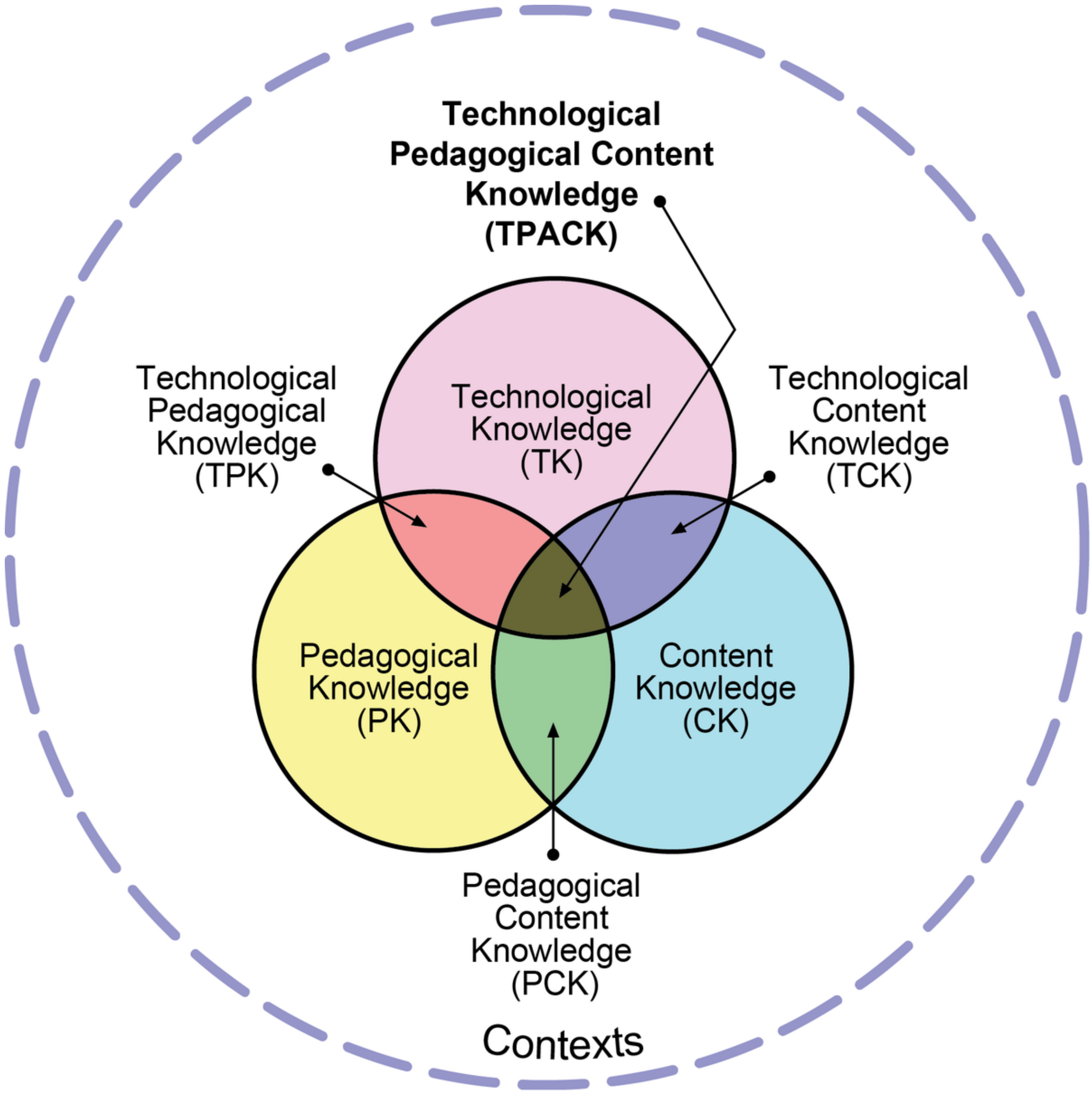


Figure 2.5: Venn diagram of TPACK as proposed by Kohler et al [104] consisting of the interplay between Technological Knowledge, Content Knowledge and Pedagogical Knowledge, all within a specific context of the use of technology in education

Additionally, the intersections of the three domains of the knowledge as visible in the venn diagram in figure 2.5 represents the interplay between these dimensions.

- **Pedagogical Content Knowledge (PCK)** refers to an understanding of how the content and pedagogical strategies are interrelated. In essence, teachers need to know the most effective ways to teach specific content.

- **Technological Content Knowledge (TCK)** is knowledge about how technology can be used to enhance the content. This could include using simulations to demonstrate scientific principles.

- **Technological Pedagogical Knowledge (TPK)** involves understanding how particular technologies can change the ways teachers teach and how students learn. It's about knowing how to select and use technological tools to enhance learning.

TPACK refers to the point of intersection of all three aspects and It's about understanding how technology, pedagogy, and content can interact to produce effective teaching and learning.

While the TPACK framework was originally conceptualized to understand the adoption of instructional technology from the educators' perspective, Benton-Borghi highlights the limitations of the traditional TPACK framework when it comes to accommodating students with disabilities, as well as its shortcomings in addressing the pedagogical variances in teaching students with diverse learning needs [22]. This discrepancy implies that the conventional TPACK framework falls short of meeting the educational standards expected of classroom teachers, particularly in inclusive settings. Additionally, it does not adequately capture the interplay between assistive technologies utilized by students with disabilities and instructional technologies employed by educators, such as projectors or 3D science models.Marino et al. highlighted the lack of preparedness among classroom teachers regarding the implementation of both assistive and instructional technologies in their instruction strategy. They attribute this deficiency to the inadequate training in assistive technology use during instructional periods, as observed in teacher training programs [127].

To address these gaps, Benton-Borghi et al. propose a modification of the TPACK framework, grounded in the principles of Universal Design for Learning (UDL), resulting in what they term "UDL-infused TPACK" [21]. In this modification to the TPACK model, 'Technology' encapsulates both assistive and instructional technologies, highlighting the imperative for educators to have a comprehensive understanding and trust in the efficacy of assistive technologies. This knowledge and belief are vital for boosting student achievement, championing inclusive education, and facilitating a seamless amalgamation of assistive technologies into the educational context.

Achieving mastery in the interplay of technological, pedagogical, and content knowledge, as outlined in the TPACK framework, is a critical benchmark for the integration stage of Kintsch and DePaula's AT adoption model. In Chapter 6, I align the findings from my research with Benton-Borghi's concept of a UDL-infused TPACK. This serves to emphasize the advancements made in my overarching research goal, which is to seamlessly incorporate the use of audio-tactile graphics within educational institutions.

2.5 Overview of Methodology

To address the three research questions aimed towards understanding a) the context in which transcription occurs, b) possible ways to situate audio-tactile graphics within current transcription practices, and c) simulating use of audio-tactile graphics in realistic context and using established practices, I employed a suite of qualitative research methods across three distinct studies. In Study 1, I engaged participants in semi-structured interviews via Zoom, allowing for an in-depth exploration of their experiences and perspectives. For Study 2, I facilitated in-person co-design workshops, which culminated in a focus group session to gather collective insights and reflections. In Study 3, I adopted a mixed-method approach, utilizing semi-structured interviews, a diary study, and reflexive memos to capture a comprehensive understanding of the participants' experiences during field deployment. All of these studies received ethical approval from the University of Michigan's Institutional Review Board, ensuring adherence to research ethics, participant privacy and safety.

2.5.1 Interviews

Semi-structured interviews served as the principal data collection method in Studies 1 and 3, facilitating the capture of participants' nuanced experiences related to producing and teaching with tactile graphics in educational settings and transcription agencies. I opted for interviews due to their effectiveness in eliciting rich, anecdotal accounts of participants' current workflows, collaborative practices with colleagues, and challenges encountered in their professional roles. The semi-structured format further enabled spontaneous exploration of novel aspects of transcription workflows, enhancing my understanding of their job roles.

Across Studies 1 and 3, I conducted a total of 31 interviews, utilizing both Zoom and in-person interactions. Participants, all of whom were 18 years or older, held diverse roles such as TVIs, transcribers, tactile graphic artists, or proofreaders, and were actively involved in the production and, at times, instruction of tactile graphics in schools or transcription agencies. In Study 1, I concluded the interview phase upon reaching data saturation, i.e. - when I observed redundancies in participant accounts to my questions, which was evident after engaging with at least six participants from schools and transcription agencies. In Study 3, I conducted weekly interviews with two participants over the duration of the field deployment of the T3, resulting in a total of 16 interviews. Participants received compensation ranging from $15 to $100 for their participation.

To facilitate analysis, all interviews were audio-recorded, transcribed, and quotations presented within this text were lightly edited for purposes of readability.

2.5.2 Co-design Workshop

Participatory methodologies, such as co-design, are vital for integrating diverse perspectives and experiences of various stakeholders, directly influencing the end-user's interaction with technology [4, 102, 122] . In Study 2, I orchestrated co-design workshops, bringing together a range of stakeholders including TVIs, tactile graphic designers, paraeducators, and access technology specialists. The aim was to comprehend their prospective use of the T3, gauge their existing knowledge and experience with tactile graphics, and discern the tools they conventionally employ for creating and teaching with audio-tactile graphics.

These workshops spanned 120 minutes each and were conducted at the Intermediate School District (ISD) offices, utilizing the available resources. I adopted the role of an audio-tactile graphic artist during these sessions, providing necessary technical support to translate participants' audio-tactile graphic mock-ups into functional T3-based graphics.

For thorough analysis, both audio and video recordings of the workshops were made, complemented by observation notes that I compiled while facilitating the workshop and aiding participants in their design process. Participants received a compensation of $60 for their contribution, and some were additionally granted work credit hours by their employers.

2.5.3 Field Deployment

The choice to offer the T3 to participants for their daily teaching practices aimed at capturing authentic insights into its utility. This decision drew from prior research, validating the T3's usability for both educators and BVI readers [135]. The version of the T3 utilized in this study was sufficiently robust, supporting real-world application scenarios. The research incorporated two TVI participants, granting them the autonomy to integrate the T3 into their teaching routines, while also utilizing their existing access technologies.

Participants underwent training on how to operate the T3 during the initial background interview sessions, utilizing training materials provided by the manufacturer. Notably, one of the participants had previously engaged in the co-design workshop study. Throughout the field deployment, I was accessible via phone to address any technical or usability concerns, and I could also offer in-person support when necessary, owing to my proximity to the deployment sites.

Consistent with the methods outlined in the previous section, the study involved conducting weekly semi-structured interviews. Additionally, diary entry prompts were employed to gather ongoing reflections and observations from the participants about their experiences and progress with their students using the T3. Participants submitted their weekly diary entries through a Google Form, which included both survey questions and open-ended prompts. The particulars of these questions are discussed in detail in chapter 5.

During the field-deployment study, my primary role was to assist educators, bridging any technical gaps that might hinder the seamless integration of the T3 into classrooms. To capture the nuances of this experience, I kept a detailed record through reflexive memos, detailing my interactions with educators, the tasks I supported them with, and observations on how the T3 compared to their existing practices. These memos were instrumental in identifying recurring challenges faced by educators, shedding light on potential refinements for the T3 system. Through these interactions, I gained a deeper understanding of educators' perspectives, underscoring the necessity of ongoing support and training when introducing novel technologies to classrooms. These documented insights highlight the pivotal role of hands-on guidance in facilitating the successful assimilation of novel assistive technologies like the T3 into educators' daily routines.

2.5.4 Data Analysis

The inductive thematic analysis was a crucial approach for deciphering the rich qualitative data gathered across the various studies. This method allowed for a structured yet flexible interpretation of participants' experiences, insights, and interactions with the assistive technologies and the audio-tactile graphics.

- **Familiarization with Data**: The first step involved immersing myself in the data. This meant repeatedly listening to the audio recordings, reading through the interview transcripts, reflexive memos and reviewing the interviewer notes. This process helped in gaining a deep understanding of the participants' perspectives, their challenges, and the contexts in which they operated.

- **Generating Initial Codes**: Based on this initial understanding, I started generating preliminary codes. These codes represented key concepts, ideas, or patterns that appeared across the different datasets. This process was iterative, requiring several rounds of revision and refinement.

- **Collaboration and Dialogue**: Collaborating with my co-authors was a significant aspect of this analysis. Engaging in ongoing dialogues ensured that our interpretations were robust, reliable, and valid. We challenged each other's assumptions, clarified ambiguities, and worked together to refine our coding framework. This collaborative process not only strengthened the reliability of our findings but also enriched our understanding of the data.

- **Theme Development**: Once we had a stable set of codes, we moved on to the theme development phase. This involved clustering related codes together, identifying patterns, and discerning broader themes that encapsulated the essence of the data. This step was crucial for moving from descriptive coding to a more interpretive, analytical level of understanding.

- **Utilizing Visual Data**: The visual data from studies 2 and 3 played a complementary role in this analysis. Videos and photographs captured non-verbal interactions, gestures, and expressions that were not accessible through audio or text alone. These non-verbal cues provided additional context, helping to enrich our interpretation of participants' experiences and interactions with the audio-tactile graphics and the T3.

- **Contextualizing Non-Verbal Cues**: Noting down non-verbal interactions, such as pointing or demonstrating gestures, added depth to our understanding. It allowed us to connect participants' spoken words with their physical actions, creating a more holistic picture of their experiences.

By employing this rigorous and collaborative approach to thematic analysis, we were able to draw meaningful insights from the data, connecting individual experiences to broader trends, patterns, and themes. This method enabled us to navigate the complexity of the participants' interactions with audio-tactile graphics and assistive technologies, offering a nuanced understanding that informed the findings of the dissertation.

2.6 My Positionality

I identify as male and I have sight and do not have any disabilities. I work as a researcher in the field of audio and tactile methods for conveying graphical content. With over five years of experience engaging with individuals with disabilities in North America, I have honed my skills in the realm of tactile and audio-tactile graphics through my doctoral research. During this period, I have supported educators in the creation of both tactile and audio-tactile graphics. Despite my extensive hands-on experience, it is important to note that I have not undergone formal professional training in the production processes of tactile and audio-tactile graphics specifically tailored for educational use.

2.7 Summary of the Chapter

In this chapter, I examine the existing body of literature on audio, visual, and tactile perception to illuminate the distinct differences between how sighted individuals perceive images and how BVI readers interpret tactile graphics. I delve into previous studies to elucidate the intricate landscape of vision impairment education programs in North American schools and to review research that includes educators in the assistive technology design process. Furthermore, I articulate my research aims within the context of these pertinent fields, offering an overview of the methodologies I employed to address my research questions. Additionally, I reflect on my stance as a researcher engaged in the participatory research methods presented in this thesis.

CHAPTER 3

Interviews with Practitioners who Transcribe and Teach Using Tactile Graphics.

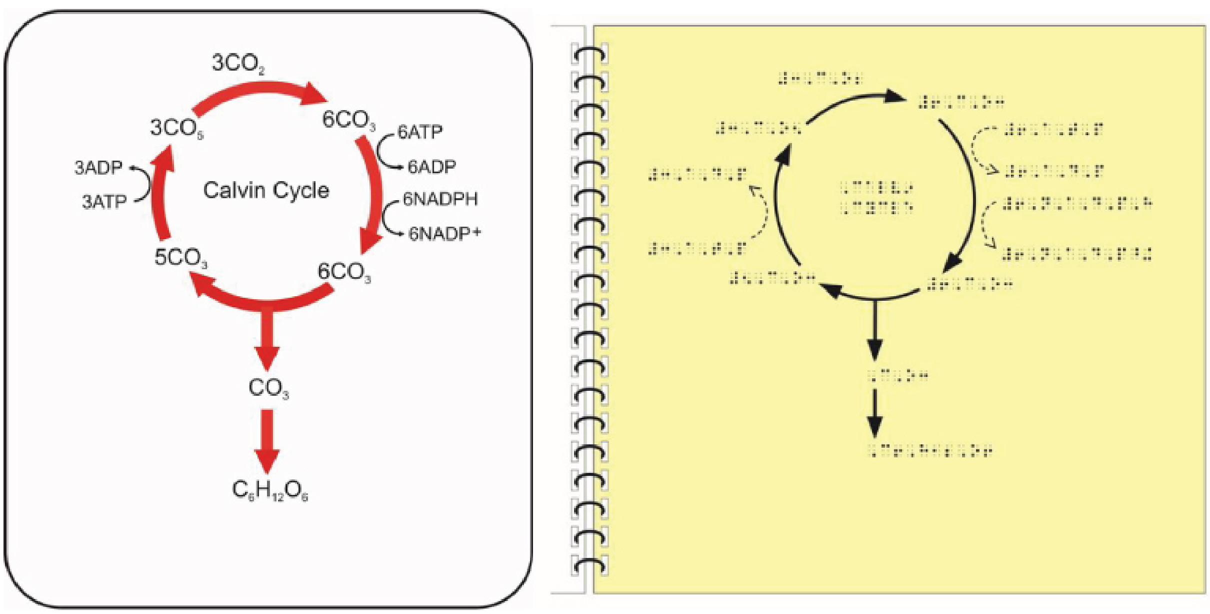


Figure 3.1: Screenshots from the Braille Authority of North America Guidelines [29]. Calvin cycle is represented as left) a print image for sighted students, and right) transcribed tactile graphic that uses raised lines and braille text to represent the concept. The tactile graphic is transcribed from the visual image by a transcription team working in schools or transcription agencies.

3.1 Introduction and Background

Visual diagrams—such as charts, maps, flowcharts, and infographics—are gaining traction as a preferred method for conveying information in a variety of print media including books, newspapers, and magazines. For BVI individuals to access these visual resources, it is imperative to transcribe them into tactile graphics—a form of tactile representation. Tactile graphics play a crucial role in facilitating the comprehension of complex information across diverse domains, such as STEM education [218], journalism [62], and the dissemination of critical data, including COVID-19 statistics [190].

The Braille Authority of North America (BANA) has proactively established guidelines[29] aimed at standardizing the design of tactile materials. These guidelines serve as a comprehensive resource for designers, aiding them in the creation of legible tactile graphics from their visual counterparts. However, the interpretation of these guidelines, especially in terms of image simplification and highlighting vital information, remains subjective [29]. Additionally, the expertise and training of the transcriber play a significant role in influencing the quality of the tactile graphic design [195].

In educational environments, tactile materials prove to be invaluable for students with vision impairments, offering them a rich and immersive learning experience. TVIs frequently incorporate these materials into their teaching methodologies to elucidate complex concepts. Nevertheless, the production of tactile materials within educational settings is often marked by its complexity, time-intensiveness, and laborious nature [218], culminating in graphics that are typically tailor-made to meet the unique needs of individual students [172]. TVIs have highlighted the intricate challenges associated with crafting meaningful tactile graphics and equipping students with the skills necessary to enhance their tactile graphic literacy [180].

Our research delves into the utilization of tactile graphic design tools within educational settings, shedding light on the socio-technical factors that influence both the transcription process and the tools themselves. This includes an exploration of factors related to specific contexts and the collaboration amongst various stakeholders.

3.1.1 Tactile Graphics Design Tool

In the domain of tactile graphics design, the choice of authoring tools is a critical factor that significantly affects the outcomes of the design process. Previous research aimed at enhancing or aiding transcribers in their task of producing tactile graphics has led to two main sets of recommendations:

- **Recommendations aiming to enhance the design quality of a tactile graphic**. These suggestions encompass the integration of automation for bolstering quality control, the establishment of pre-defined design guidelines for lines and filling patterns

[164], the development of training materials tailored for designers [152], and the formulation of specific design guidelines pertinent to STEM-related graphics [56, 57] .

- **Recommendations focused on optimizing the overall workflow associated with tactile graphics production**. This includes the innovation of tools that facilitate "rapid-prototyping", enabling swift image editing and the seamless addition of braille labels [130, 161], as well as advocating for the design of supportive systems such as image libraries [152]. The latter aims to encourage the reuse of existing tactile graphics, fostering a culture of efficiency and resourcefulness.

Despite these advancements, previous discussions on the usability of tactile graphics design tools have tended to overlook the complex workplace factors that play a critical role in shaping the workflow and the ultimate design of tactile graphics. It is crucial to address this gap to ensure a holistic understanding and improvement of the tactile graphics design process.

3.1.2 Challenges in Producing Tactile Graphics

In an educational setting centered around visual learning, students with visual impairments are often required to attain a level of mastery in interpreting tactile graphics before they can delve into STEM subjects. Achieving proficiency in this area is a long-term endeavor, necessitating engagement with tactile graphics from a young age [172]. Unfortunately, this demanding prerequisite contributes significantly to the underrepresentation of BVI individuals in STEM fields [83]. Existing research tells us that students with visual impairments seldom receive comprehensive training in reading tactile graphics, resulting in a general reluctance to utilize these resources [172]. Transcribing complex or densely packed images poses a formidable challenge for educators [131], while also being difficult for students to interpret [164]. Investigations spanning various North American schools have uncovered a pervasive lack of adequate training, experience, resources, and time among teachers, hampering their ability to generate tactile graphics within an educational setting [223].

While the BANA guidelines provide comprehensive instructions for creating tactile graphics, they do not offer specific guidance on instructing students in the interpretation of these graphics nor on tailoring graphics to meet individual learning styles. This gap highlights the urgent need for further research to fully comprehend the distinctive challenges and support needs faced by educators in this area. Additionally, there is a notable lack of research into the contextual elements that shape the transcription workflow and, by extension, influence the design of tactile graphics themselves. Such factors include collaborations with third parties, workplace-specific considerations, and the dynamics between educators and their students.

This study aims to shed light on the contextual factors that, while not directly related to a student's ability to understand tactile graphics or their individualized learning needs, impact the strategies that educators adopt when both creating and teaching with tactile graphics.

In the process of transcription, specialists in tactile graphics engage in collaborative efforts with various external stakeholders, including classroom teachers, representatives from client schools, and experts in specific subject matters. Despite this, there exists a noticeable gap in our comprehensive understanding of how these external collaborations and interactions influence the design of tactile graphics during the transcription phase. Addressing this necessitates a thorough examination of the points of interaction between the transcription process and other operational facets within an organization, such as Independent School Districts (ISDs) or individual transcription agencies. In Michigan, ISDs are typically county-level entities that support local schools by providing a spectrum of educational programs and services.

3.1.3 Tactile Graphic Specialists

Prior research has delved into developing tools aimed at enhancing the tactile graphic transcription workflow. In our study, we draw upon Ladner et al's six-step procedure involved in creating tactile graphics, comprising image tracing, image labeling, designing and developing the key, marking the key, making the key, and finally, printing the key, collectively referred to as the Translation Task Flow (TTF) [111] (ref figure 2.1). Although the complex and iterative nature of this process makes it challenging to directly associate these steps with specific job roles, we have been able to identify five prominent roles based on surveys conducted with professionals in the field of tactile graphic transcription [161, 111]: *Transcribers, Paraeducators,TVIs, Tactile Graphics Artists,Assistive Technology Specialists.*

3.1.4 Research Questions

Our study involved interviewing 13 educators across US and Canada to gain insights into their experiences with the tactile graphic transcription process, their collaborative practices, and the challenges they face during these interactions. This research is guided by the following questions:

- RQ1: What context-specific factors influence the way tactile graphics specialists transcribe visual images into tactile graphics within an educational setting?

- RQ2: What are the context-dependent challenges faced by tactile graphics specialists during the transcription process?
- RQ3: What possibilities exist for mitigating these challenges through the integration of emerging technologies, the establishment of new design guidelines, or the adoption of innovative reproduction processes?

To address Q1, we conducted a series of interviews with tactile graphics specialists, focusing on their collaborative interactions with stakeholders and the unique factors introduced by the transcription setting. For Q2, we scrutinized the areas of difficulty highlighted by our participants in their respective workplaces. Lastly, to tackle Q3, we delved into why these areas of difficulty merit attention and proposed recommendations aimed at alleviating the concerns of our participants. Our suggestions are grounded in the latest advancements in research pertaining to tactile and audio-tactile graphic production technology.

3.2 Methods

We carried out semi-structured interviews as a means of gathering qualitative data, and subsequently conducted an inductive thematic analysis on the transcribed interviews. The themes that surfaced from this analysis form the basis of this paper, specifically concentrating on elucidating the factors that impact practitioners' design decisions and workplace elements that shape the transcription workflow.

3.2.1 Participants

We engaged in a systematic participant recruitment process, extending invitations via email to our contacts within the field, including TVIs, transcribers, and proofreaders. Our efforts also included outreach to users sharing tactile graphics content on Instagram and making contact with agencies listed on reputable websites such as the National Federation of the Blind (NFB).

Our study involves interviews with a total of 15 participants, though the data from only 13 individuals was included in the final analysis. The criteria for participation required individuals to be at least 18 years of age and actively working as a TVI, transcriber, tactile graphic artist, or proofreader, whether in a transcription agency or educational institution. Two participants, both highly experienced veteran transcribers who had ceased active transcription work, were excluded from the analysis. Our rationale for this decision was to prioritize insights from current practitioners, ensuring the relevance and immediacy of our findings.

Nevertheless, consultations with these veteran transcribers were invaluable for gaining a comprehensive understanding of the transcription process and interpreting our data, as their seasoned perspectives helped us to frame our results within a broader context.

From the participants included in our analysis, 5 identified as male and 8 as female. Professionally, the group was comprised of 5 TVIs and 8 individuals engaged in roles as transcribers, proofreaders, or both. In terms of workplace settings, 7 participants were employed at transcription agencies, while 6 worked within schools or universities.

Table 3.1 presents a more detailed breakdown of our participants' demographic information, including their job roles, ages, and years of experience in the field. This additional data serves to enrich the context of our findings, offering readers a comprehensive view of the diverse range of professionals contributing to this study.

3.2.2 Interviews

For this study, we utilized online semi-structured interviews conducted via video and audio calls to gather data. Throughout these interviews, participants were prompted to share their personal experiences in the creation and instructional use of tactile text and graphics. We posed questions that encouraged participants to delve into their processes of designing tactile graphics, exemplified by queries such as "Can you walk me through the steps you took in your most recent transcription project?"

Additionally, participants were urged to reflect on and articulate the decisions they made during the design phase of tactile graphics, as well as the elements that played a role in shaping these decisions. In order to garner insights into their design and proofreading rationale, we asked them to recall specific instances and detail the thought process behind their actions, exemplified by questions like "Can you recall the last time you had to verify the effectiveness of a transcribed chart? How did you approach this?"

These inquiries were aimed at eliciting rich, detailed accounts of their experiences, providing us with a comprehensive understanding of their work processes and the considerations that influence their practice.

3.2.3 Data Analysis

The team employed inductive thematic analysis to dissect the data, adhering to the methodology discussed by Braun and Clarke [32]. To initiate the analysis, one research team member meticulously reviewed the interview transcripts as well as the interviewer's notes to gain a comprehensive understanding of the data.

Table 3.1: Study 1 Participant Demographics

P #	Visual Impairments	Gender	Years of Experience	Age	Job Title	Workplace
P1	Visually Impaired	Male	10	51-65	Proofreader	Agency
P2	Sighted	Female	5	24-30	TVI	School
P3	Sighted	Female	15	41-50	TVI	School
P4	Sighted	Female	15	31-40	Transcriber	School
P5	Sighted	Female	10	31-40	Transcriber	Agency
P6	Visually Impaired	Male	20	41-50	Proofreader	Agency
P7	Sighted	Female	10	51-65	Proofreader	Agency
P8	Visually Impaired	Male	15	41-50	Proofreader	Agency
P9	Sighted	Male	30	51-65	Proofreader	Agency
P10	Sighted	Female	10	31-40	TVI	School
P11	Sighted	Female	10	31-40	TVI	School
P12	Visually Impaired	Male	10	51-55	Proofreader and Transcriber	Agency
P13	Sighted	Male	8	31-40	TVI	School

In the subsequent phase of analysis, the same researcher developed an initial set of codes, applying them to the entire dataset, which comprised both the transcripts and the interviewer's notes from all conducted interviews. Next, the research team engaged in recursive discussions, during which they meticulously refined these codes, ensuring they accurately represented the nuances of the data.

Following this, the entire research team collaboratively sifted through the preliminary codes, grouping them into themes based on their relevance and causal relationships. This rigorous process culminated in the emergence of six distinct themes, which served to categorize the participants' experiences and insights:

- **Factors Affecting Design**: factors that were discussed to influence how participants designed tactile graphics.
- **Criteria for an Effective Tactile Graphic**: comments about the attributes that contribute to the usability and effectiveness of tactile graphics.
- **Stakeholder Needs and Requirements**: comments addressing the diverse expectations and necessities of all parties involved in the tactile graphics process.
- **Information Inclusion/Exclusion Criteria**: comments outlining the decision-making process for determining what information is retained or omitted in the final tactile graphic.
- **"Work" Performed Besides Transcribing**: Highlighting additional tasks and responsibilities undertaken by participants, beyond their typical transcription tasks.
- **Barriers and "What Would You Do Differently?"**: Identifying challenges faced during the tactile graphics process and soliciting insights on potential improvements or alternative approaches.

These themes served as a framework for interpreting the data, providing a structured lens through which the research team could examine and understand the complex realities of designing and utilizing tactile graphics.

3.3 Findings

In this section, we present a synthesis of the insights gained from a thematic analysis of the interview transcripts. We have categorized our findings into two overarching socio-technical factors that influenced our participants' decision-making processes and workflows related to the transcription of tactile graphics:

- **Collaborations With External Stakeholders**: This factor examines the influence of collaborative interactions with individuals and entities beyond the immediate transcription team but who are key stakeholders in the process of teaching with tactile graphics. External stakeholders can include educators, students, and other professionals who play a role in determining the requirements and specifications for tactile graphics. Understanding the needs and expectations of these stakeholders is essential for our participants because it directly shapes the design choices and alterations applied to the tactile graphics. Moreover, these collaborative steps are frequently overlooked in numerous studies that regard transcription merely as the process of converting images into tactile formats (such as in [110]).

- **Workplace-Specific Transcription Processes**: This aspect explores the unique procedures and practices that are inherent to the participants' work environments, whether in a school district office or a transcription agency. The way tactile graphics are designed and produced can vary significantly based on the workplace. By examining these workplace-specific processes, we gain insight into the diverse workflows for producing tactile graphics and identify potential areas for improvement and standardization.

By focusing on these socio-technical factors, our analysis sheds light on the complexities of designing educational tactile graphics, highlighting the need for a holistic understanding of both the social and technical dimensions that shape this practice.

3.3.1 Impact of External Stakeholders

The Translation Task Flow (TTF) by Ladner et al. [111], outlines the sequential steps educators undertake while transcribing tactile graphics. Our participants confirmed they followed a comparable workflow but noted extra steps for collaboration with external stakeholders who, while not directly involved in the core design process, are nonetheless crucial in practical scenarios, as we glean from our participants' experiences detailed below. Employing the TTF flowchart, we position these collaborative efforts in relation to the steps traditionally considerd to be a part of the transcription process. To thoroughly represent these interactions, we suggest the inclusion of three ancillary steps in the TTF:

3.3.1.1 Obtaining Well Formatted Source Material.

To initiate the first stage of the Translation Task Flow (TTF), which involves planning the design of a tactile graphic, the transcription team needs to acquire the original image.

They also need to understand the context in which the image will be used and identify the target audience. This information is typically provided by classroom teachers, paraeducators, and client organizations during initial meetings. P4 highlighted the importance of these discussions is in trying to *"figure out exactly what the client wants - why they want it - so that we can provide the best tactile graphic or best tactile map for their purposes and their audience."* Participants P3, P4, P5, P7, and P8 reported engaging in similar initial meetings with their respective client organizations and classroom teachers.

Our participants highlighted challenges related to acquiring source material in a format that is compatible with their preferred design tools and free of errors. P1, a visually impaired braille text transcriber, shared their experience with receiving incorrectly tagged support documents from clients:

> *"Sometimes I know that I'm going to want to do a lot of fixing [...] maybe the person (client) didn't know much about using proper word tags to format documents".*

This frustration with cleaning poorly formatted source materials was a common theme across participants. P7 pointed out:

> *"There's an obvious failing [...] they think they're saving time for themselves (by providing poorly formatted files), but they're ultimately adding costs to the transcription process. I'm sure you must have heard this from other transcribers too."*

The issue of cross-compatibility of source materials in the process of transcribing visual images to tactile images is a significant challenge, relying on a variety of technologies from software used to prepare adapted source images to the hardware used to render these images in tactile form. However, this problem remains an underexplored area in HCI and CSCW literature on transcription.

3.3.1.2 Education and Accessibility Awareness

Participants in our study were involved in tasks that required them to address and correct misunderstandings held by external stakeholders regarding the use of tactile graphics by visually impaired readers.

Those working in transcription agencies often found their initial meetings with clients to be *'really cringy"* and evolving into *"an education process"*, primarily due to a lack of awareness about disability and visual impairment on the part of the clients. P5 shared a vivid example, describing an interaction with a client who requested a 'you-are-here' map for an outdoor trail. The client believed *"blind hikers may not want to be at a vista point"* and was insistent on this perspective. In another instance, when a client wanted to use different braille fonts to fit more content on a page, P5 had to clarify:

> *"I had to tell them the Braille only has one font, you know. Braille has to be a particular size for vision-impaired people to read it."*

These instances underscore the duties of transcription team members within agencies to rectify clients' misunderstandings about tactile content and to mediate the development of viable project designs and deadlines.

Similarly, participants employed in schools played a crucial role in assisting classroom teachers to adopt accessible teaching methods that complemented the use of tactile graphics for visually impaired students. P10 detailed their approach, stating:

> *"at the beginning of the year we do like to meet with each of the general education teachers and we want to explain to them about what we know about our children's visual impairment, how it will impact their ability to do work in the classroom we talk about their accommodations [...] usually at that point, the teacher has concerns like 'oh, how are they going to be able to access this math activity'. So we usually just talk about how as the year goes on, we can collaborate and make sure that our students are able to participate and access, whatever it is."*

This proactive approach, also adopted by P2 and P3, ensures that general education teachers are well-prepared to support visually impaired students in their classrooms.

These narratives highlight the critical role that transcription teams fulfill in crafting inclusive educational settings, affirming that students with visual impairments receive the requisite support when reading tactile graphics. This step is also fundamental as tactile graphics are tailored to particular tasks and pedagogical strategies; thus, for their efficacy, it is crucial that teachers possess a comprehensive understanding of their instructional use [217, 180].

3.3.1.3 Collecting Student Feedback

Participants who were actively engaged with students highlighted the importance of collecting feedback to enhance the quality of tactile graphics. They emphasized that this feedback is vital for tailoring the tactile graphics to the individual preferences of the students. One common practice for obtaining this feedback was during *"pre-teaching"* sessions, where educators introduced the tactile graphic to the student before it was used in class. P10 shared their experience, stating:

> *"there's nothing that brings them [the students] more joy than finding out when we [TVIs] make an error. Something we [TVIs] can tell, is the height [of a line], but for him [the student] to feel that was confusing, so we have to make that line a different texture. We might use some embossing tape or wiki stick to delineate that particular line from this, the actual triangle."*

In this context, "error" refers to a design decision that involved using different line heights to define the boundaries of a triangle and another line dividing it in half. The student struggled to differentiate the line heights, prompting a change in the texture of the dividing line. Participants like P10 and P2 utilized rapid prototyping materials, such as 'wikki stix' and tactile stickers, for on-the-spot modifications to existing tactile drawings.

In contrast, transcribers in agencies seldom had direct access to their end-users, typically students. In the mass production of transcribed graphics at transcription agencies, tactile graphics undergo a proofreading process to ensure quality and accuracy before being distributed to schools. Professional proofreaders play a crucial role in verifying that the graphics effectively convey their intended meaning and are user-friendly. P4 outlined their collaborative process with proofreaders, noting that they would:

> *"print out and emboss samples for [in-house proofreader], to look at as we're going through the design process we do those weekly design meetings."*

Similarly, P7, whose desk was only *"feets apart"* from their proofreader, mentioned, *"even when in progress, I can print the work in progress and ask how do you like this design."* On the other hand, transcribers like P9, who is sighted and proficient in braille and tactile graphics, took it upon themselves to meticulously proofread their work before presenting it to clients. When asked about potential improvements to their current design process, numerous participants expressed a wish for *"getting more interaction with the end users [P4]"* and an opportunity to collect feedback.

In summary, this section introduces three additional steps to the TTF in an educational context: **formatting source files, educating stakeholders about accessibility, and gathering student feedback**. These expanded TTF steps highlight the potential for design tools to facilitate collaborative interactions between educators and external stakeholders, a topic we explore further in the discussion section.

3.3.2 Workplace-Specific Transcription Processes

We discovered that the transcription processes our participants followed varied significantly depending on whether they worked in agencies or were embedded within educational institutions such as schools and universities. These variations could be categorized following several broad socio-technical themes:

3.3.2.1 Work Structure

Our participants embedded in schools and universities acted as intermediaries between classroom teachers and BVI students. They initially assessed the needs of the students, grasped the educational goals of the classroom teachers, and subsequently crafted tactile graphics that catered to the necessities of both parties. On the other hand, participants from agencies characterized their clients (schools requiring the transcription of visual materials) as serving as the conduit between educators and end-readers. In this workflow structure, the clients conveyed the needs of the readers to the transcribers, retrieved the transcribed materials from the agency, and then distributed them to the VI readers. This distinct structure is depicted in Figure 3.2.

The organizational structure of transcription specialists and other stakeholders significantly impacts the transcription process. P1, who worked at an agency, highlighted this by stating:

> *"if you're somebody who has a working knowledge of the subject, you can probably make somewhat better decisions about what information needs to be provided."*

We interpret this statement to mean that possessing subject knowledge enables a transcriber to more accurately interpret the visual graphic, ultimately transcribing it into a tactile graphic that communicates the intended meaning in the most effective way possible.

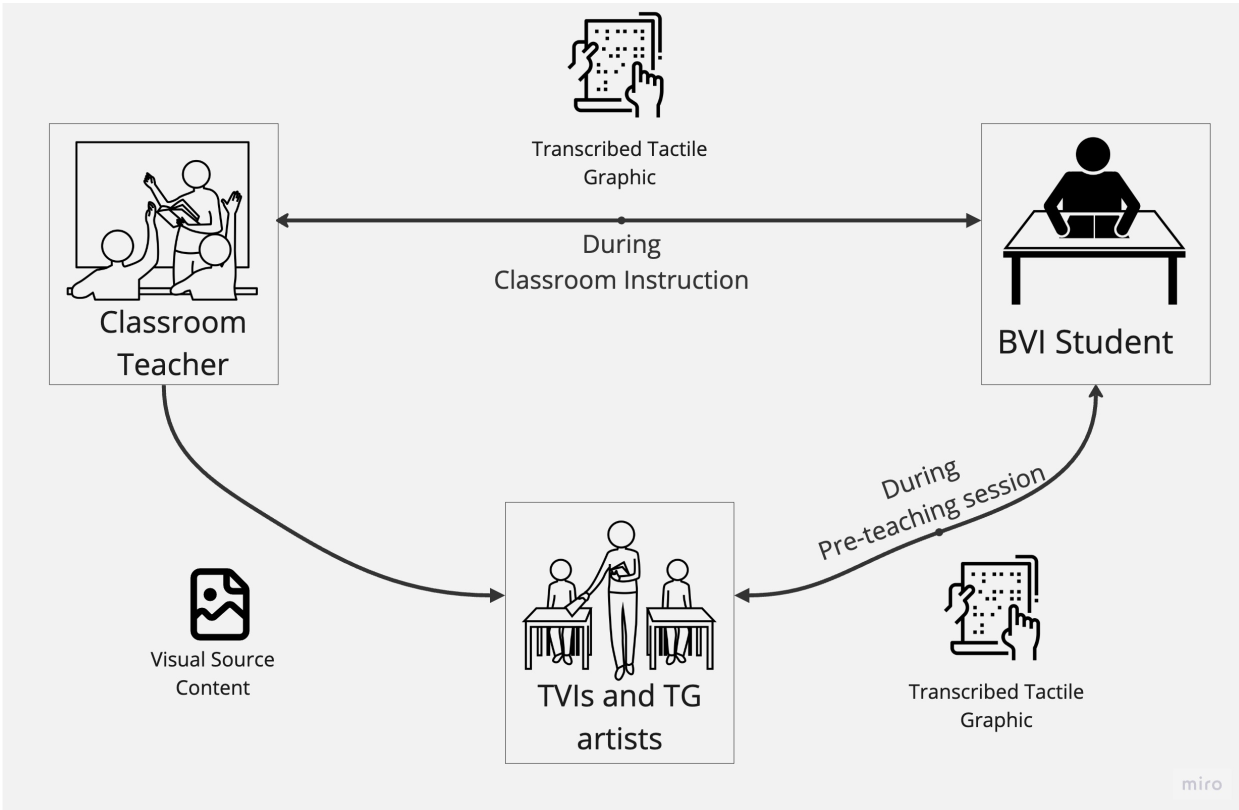
Similar to P1, P9 from an agency shared their reliance on personal experience and skills when asked about evaluating the effectiveness of a transcribed graphic:

> *"I rely on my experience and my Braille sense. [...] You really learn how to drive a car after you get your license. And you really learn how to draw after you get your certification."*

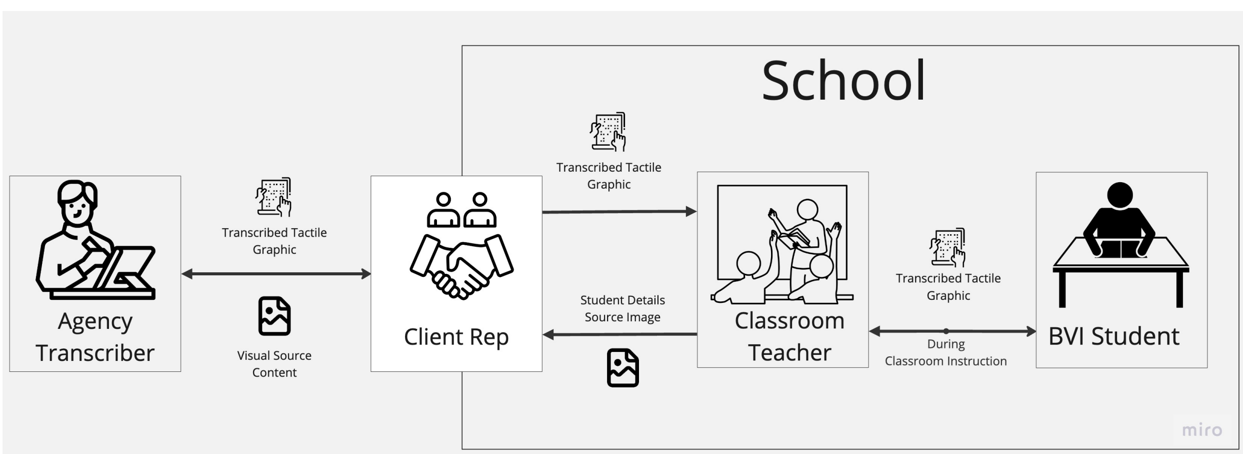
This perspective differs significantly from P3's experience - who worked at a university:

> *"we have a zoom meeting with the teaching staff, they tell us 'hey this is how, this diagram can be better represented as a table' and so after we learn from the professor how to do those we do them."*

In P3's case, direct input from teaching staff played a crucial role in shaping the design of the graphic, highlighting the importance of collaborative design decisions, especially when



(a) Figure A: Workflow Structure in A school Setting.



(b) Figure B: Workflow Structure in a Transcription Agency

Figure 3.2: An illustration depicting the transcription workflow structures in schools and agencies. Transcription teams in schools are more integrally involved in the use of tactile graphics, whereas agency transcribers are positioned externally from the instructional process involving tactile graphics.

dealing with complex university-level STEM course materials. P3 also emphasized reaching out to the teaching team for content-related queries, given their lack of subject matter expertise.

3.3.2.2 Measuring Readers' Skill

It is crucial to take into account the reader's proficiency in interpreting tactile graphics while creating a graphic tailored to their needs. The approaches adopted by educators in schools and agencies to address this vary significantly.

Educators working within schools and universities emphasized the use of assessment tests (sometimes also referred to as placement tests) to gauge a student's tactile graphic reading skills. P10 detailed their approach:

> *"We use assessment tools and age-appropriate checklists that help guide us in understanding what skills a student possesses, and to know what kind of skills each child should have at different ages."*

Such systematic evaluation aids in determining the level of complexity and the production techniques to be employed for the tactile graphic. P11 provided further insight:

> *"Depending on the grade, a student will use their learning tables that Duxbury provides. In the initial stages of learning Braille, they may only be on Grade one or uncontracted Braille, so they need to learn those extra contractions. We'll use the learning tables in Duxbury to teach the extra contractions that they're just learning, without exposing them to fully contracted Braille straight away."*

On the other hand, participants P1, P4, P5, P6, and P7, affiliated with agencies, depended on the client's information about the end-reader or made informed assumptions based on the content material, often not having direct access to the end-users themselves. P4 shared their strategy when designing tactile maps for public spaces, catering to a broad audience:

> *"We try to assume that someone has never read one of our maps, or perhaps any tactile map before. So, we aim to make it as straightforward to understand as possible. For instance, in a children's museum, we anticipate that the kids are probably too young to have encountered maps in school yet. This becomes a teaching moment, where a parent or docent can guide the child's hands to the Star, explaining that the star symbolizes 'you are here', indicating our current location."*

P4, from an agency, envisions utilizing tactile graphics as a tool to enhance a student's tactile reading abilities, aligning their goals with those of participants like P11 in educational settings.

In conclusion, participants across the board stressed the necessity of creating graphics that are in sync with the readers' abilities. They collectively conveyed the message that their intention behind designing graphics is to support novice readers and to assist beginners in improving their skills. Nevertheless, transcribers who are distanced from their end-readers often lack access to vital information about the readers' tactile graphic skills. This highlights the need for two different sets of prerequisites for transcribers, regardless of their use of the same design tools.

In the discussion section, we explore the potential for developing tactile graphic design tools to aid educators in a) obtaining feedback on their designs from students and b) acquiring a more intuitive understanding of a student's current tactile skills and the means to track their progress. Needless to say, such tools should facilitate the utilization of existing design guidelines while also accommodating new guidelines for specific usage contexts.

3.4 Discussion

Our discussions with participants from various workplaces consistently touched upon a common set of tactile graphic design tools: MS Word, Adobe Illustrator, Corel Draw, and Duxbury, tools that have been acknowledged in previous studies involving tactile graphic transcribers [161]. Nonetheless, this paper brings to light two crucial workplace-specific subtleties that influence how designers utilize these tools: the nature of collaborations with external stakeholders throughout the design process, and the distinct transcription workflows characteristic of each workplace. In this discussion, we unpack the potential for ongoing research in the space of tactile graphic design tools to address and accommodate these specific nuances.

3.4.1 How can Tactile Graphic Design Tools Support the New TTF

We've suggested three enhancements to Ladner et al.'s Translation Task Flow (TTF), aiming to better cater to the collaborative nature of transcription in educational settings, particularly schools.

The first of these enhancements introduces a step for **obtaining well-formatted source files** from clients. The challenge of cross-compatibility in source files has been a topic

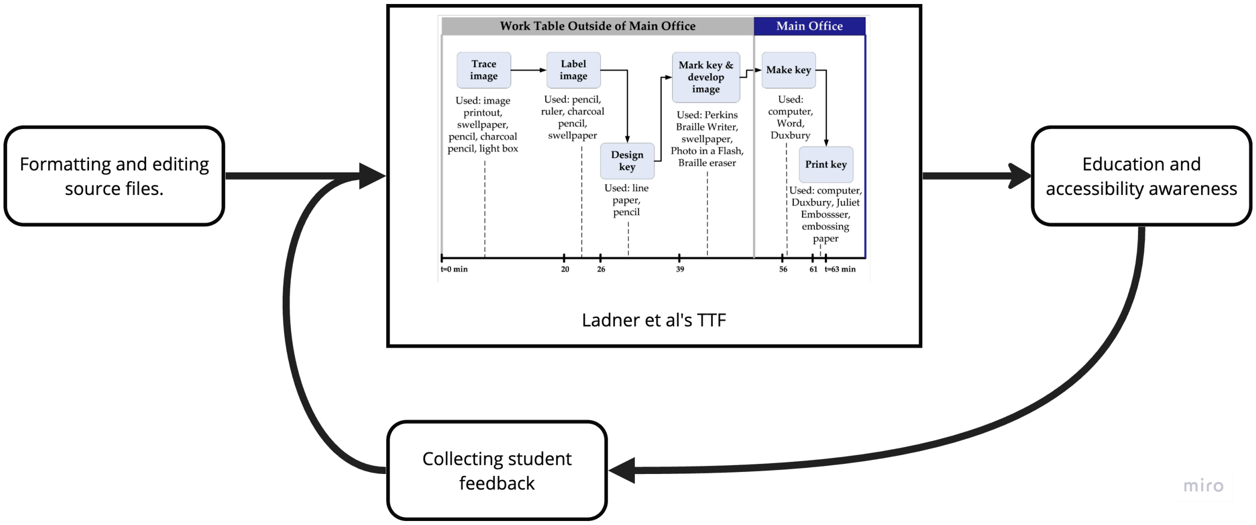


Figure 3.3: Flowchart of the New Translation Task Flow (New TTF), incorporating pre- and post-production steps to enhance the scope of steps that is typucally considered part of the transcription workflow followed by educators in schools

of discussion in previous work, particularly in the context of automation and the reuse of materials. For graphics that are frequently used and repurposed, establishing online repositories of tactile image files available for download in various formats has proven to be an effective strategy in increasing the accessibility of tactile graphics for educators [39]. In scenarios where clients provide source files, previous research on automating the TTF, such as the Tactile Graphics Assistant (TGA) described in [65], have suggested methods by which systems might offer an initial draft of a transcribed graphic, subject to further revision by a human transcriber. It is crucial that tactile graphics design tools support educators in both of these sites, and we encourage designers of tactile graphics design tools to consider ways in which a combination of these proposed solutions could assist educators in obtaining well-formatted source files.

The second addition we propose focuses on education—specifically, raising awareness about **accessibility awareness, among external stakeholders**. Kahn & Lewis have demonstrated that STEM teachers often feel ill-equipped to instruct visually impaired students [95]. Furthermore, there are relatively few TVIs available to attend science classes and provide necessary assistance to these students [102]. This results in a systemic inaccessibility in STEM education, as advances in access technologies have not yet enabled BVI students to participate in STEM education with the same level of independence as their sighted peers. Rosenblum et al. emphasize the critical importance of "intentional communication between the general education science teacher, teacher, and paraeducator" in guaranteeing accessible learning experiences for students [172]. Incorporating general education teachers into the

TG transcription process and engaging them in design represents one approach to better preparing classroom teachers for accessible instruction. However, this is a complex issue that warrants further investigation beyond the scope of this study.

The third enhancement we propose to the TTF involves enabling educators to **gather feedback from students**, facilitating the personalization of design. We explore this challenge in the context of emerging digital access technologies, such as refreshable tactile displays and audio-tactile displays [222]. These technologies are recognized for their interactivity and capability to support on-the-fly manipulation of graphics [39]. We encourage researchers to view refreshable tactile displays not just as presentation tools, but as authoring tools, empowering teachers and students to modify, refine, and tailor graphics in the classroom setting. Previous research on digital tactile displays, such as ShapeCad from [191] —a 2.5D tactile display that facilitates the creation of 3D CAD models by BVI individuals—has successfully demonstrated the use of these displays for authoring or modifying 3D models and tactile diagrams. These interactions could be effectively leveraged when integrating feedback gathering into the new TTF, fostering a more personalized and responsive educational experience.

3.4.2 How can Tactile Graphic Design Tools Support Different Workplace Structures

Our research findings have elucidated that the TG transcription process within schools is distinct from that in transcription agencies due to the close collaboration with students, which impacts the manner in which graphics are taught. Recognizing that "pre-teaching" plays an essential role in enabling students to actively participate in classroom instruction using the tactile graphics that are produced for them [172], our study observes varied approaches in design for independent reading scenarios, such as books or homework. Transcribers often resort to incorporating 'transcriber's notes' to introduce the graphic, although this method risks verbosity as the complexity of graphic images increases. P2 highlights this challenge while discussing the difficulty in conveying three-dimensional concepts through 2D graphics: "*you know such a note to imagine a 3D version of a 2D diagram is typical to 3D diagrams. I mean it's really hard to convey a three-dimensional concept on 2D graphics and a note.*" This underscores the potential of interactive tactile displays and audio-tactile displays, which can facilitate guided exploration for novice readers engaging with graphics independently [168, 41, 221]. We revisit the potential of guided exploration as part of our investigation with audio-tactile graphics in our subsequent efforts assessing their utility in the wild, covered in Study 3 (section 5.4.3.5)

The process of assessing tactile graphic and braille literacy before designing tactile graphics also diverges between TVIs in situ and independent transcribers in agencies. In this study, our school participants discussed employing assessment tests for measuring tactile acuity and student grade level to gauge a student's braille and tactile literacy, yet a standardized method for determining tactile graphic literacy remains elusive. It should be noted that tactile acuity may not always correlate to tactile graphic literacy. Transcribers in agencies often rely on proxy indicators such as student grade to make initial assumptions about tactile graphic literacy, but developing a comprehensive understanding of a student's expertise in tactile graphic and braille reading requires ongoing interaction. This presents an opportunity for the creation of a practical framework designed to guide designers and monitor student progress over time, addressing the need for standardized tactile literacy assessment tests.

In summary, our findings contribute to discussions on how tactile graphics tools may enhance workflows in both agencies and schools. Nevertheless, the issues delineated above transcend the scope of tactile graphic design tools. The efficacy of any such tool in practical application is contingent upon addressing critical research inquiries such as: How can we more effectively gauge tactile graphics literacy to personalize tactile graphics for individual students? What methods can enhance collaboration between transcription teams and external stakeholders? Additionally, how can we gather feedback from students for transcribers who lack direct access to the students for whom they design graphics?

Pursuing these inquiries is vital for advancing the ongoing development of resources and strategies to bolster instruments for measuring tactile graphic literacy and using such data during transcription within educational contexts. In the survey by [58], the emphasis on effective collaboration between general education science teachers, teachers of students with visual impairments, and paraeducators is highlighted, emphasizing its crucial role in providing timely and necessary adaptations for students with visual impairments. This collaboration ensures that adaptations are not just made but are also utilized effectively during instruction, benefiting the students' learning experience.

Our observations align with these findings, underscoring the importance of collaboration in supporting students with visual impairments. Additionally, we identified specific points where transcription and coding tools can enhance this collaborative effort.

Given the nuanced differences in workplace collaboration, it becomes evident that two transcribers might utilize the same transcription and coding tool in diverse ways. This variation underscores the need for designing transcription tools that accommodate a range of workflows, including the specific steps that occur before and after the tactile graphic design process.

Therefore, it is crucial for transcription tools to be designed with flexibility and adaptability in mind, ensuring they support the diverse needs of transcribers and educators across various collaborative settings. This approach will not only enhance the effectiveness of the collaboration but also ensure that the educational needs of students with visual impairments are met more efficiently.

3.5 Summary of the Chapter

This thesis investigates the expansive educational ecosystem that encompasses the use of tactile and audio-tactile graphics, pinpointing transcription agencies and schools as the pivotal workplaces for generating graphics for BVI students. This chapter outlines the study aimed at discerning the various workplace-based factors that could influence the transcription workflow and the selection of tools. Interviews with transcription team members in both schools and agencies have brought to light unique workflows that shape their transcription tasks, even when identical tools are employed. Both sites hosted distinct workplace structures that affected the insights and decisions that transcription teams made to create their graphics. The variations meant that professionals had access to different set of information points when making the decisions necessary for designing tactile graphics. This informs us about the importance of workplace context when understanding the requirements of a tactile graphics design tool. In the next chapter, the research will focus more narrowly on schools as transcription sites, investigating the capacity of educational ecosystems to facilitate the creation of audio-tactile graphics for use with the T3 tablet.

CHAPTER 4

Designing Audio-Tactile Graphics on T3 With Educators. [1]

Figure 4.1: Participants from one of the sessions of the user study demonstrating their audio-tactile graphic which they produced for the prompt we provided to them in the study

4.1 Introduction

The presence of graphical information is ubiquitous in both print and digital media. Graphics are essential tools for conveying information that can be understood quickly and clearly at a glance. The ability to interpret graphics is crucial in many fields, including STEM, social science, and economics, and is an essential skill for a career in such fields.

Tactile graphics are often the primary means of making information that is encoded in visual media accessible to individuals with vision impairments through touch. Tactile graphics

[1] This chapter contains text that is part of a submission to CHI 2024 proceedings, and is awaiting reviews

are images created using raised tactile lines and patterns, as well as braille text that represents an illustrated image. The ability to read and interpret tactile graphics has become a critical skill for people with blindness and visual impairments. In schools across North America, TVIs are responsible for teaching the skills required to read tactile graphics as part of the Expanded Core Curriculum (ECC). Previous research has shown that translating visual images into tactile graphics can be a time-intensive task for educators. [180]. One reason why they can be time-intensive for designers is because print images must often be simplified before they are translated into tactile graphics[29]. For example, overlapping text and color is common in print images. However, when creating tactile graphics, it is important to ensure that there is sufficient space between two distinct tactile patterns, otherwise the patterns can be difficult for BVI readers to distinguish[29]. Figure 2.2 highlights the degree of simplification between the original visual image and the transcribed tactile map of the University of Michigan central campus. The tactile graphic was produced by the widely recognized tactile mapping service, TMAP [117], which uses open street map data for source image. Designers are required to declutter such complexities when transcribing. The resulting tactile graphic that is meant for a BVI reader may lack all the details that are available to sighted students using the print version.

One way to convey the same amount of information as a printed image in a tactile graphic is through the use of audio announcements and tones. This variation of tactile graphics is referred to as audio-tactile graphics. While extensively studied in the HCI literature [45, 148, 168, 69, 88, 125, 79, 133], audio-tactile graphics are not as commonly used in schools as tactile graphics, since they are not commercially available for schools at the time of this study.

Due to their novelty, we currently lack a clear understanding of how educators and their students can benefit from audio-tactile graphics that present more information than traditional tactile graphics. Our task-based user study, consisting of a design workshop followed by a focus group is aimed at exploring this gap in the literature. The following research questions guided our study:

- **RQ1**: How would TVIs design audio-tactile graphics that meet their teaching requirements?
- **RQ2**: How would TVIs collaborate with other educators, such as classroom teachers, tactile artists, access technology consultants, to teach using audio-tactile graphics?

To answer RQ1, our participants created an audio supported tactile graphic on a T3 audio-tactile tablet (fig:1.3) based on a design prompt and following the process they typically follow when producing tactile graphics. To answer RQ2, we observed participants collaborate to create the tactile overlay, justify their reasoning behind authoring corresponding audio-labels. We also conducted a focus group at the end of the design workshop to discuss the way our educators would teach using the graphic they produced.

The T3 tablet system includes a tactile overlay, a tablet with the T3 application, and a database of unique audio-label sheets associated with each tactile overlay. To download the associated audio-label files, the T3 application reads a unique QR code associated with each tactile overlay when the reader places the overlay on the tablet. Users can query for audio labels by pressing with one finger at any location on the tactile overlay to have the corresponding audio label announced. Audio-tactile sheet authors can organize audio labels across multiple layers, which are cascaded such that every time a user presses at a location, the system reads the next layer of audio-labels until it reaches the last audio-label. The T3 is a modified version of the TMAP audio-tactile tablet. The TMAP device was developed in partnership with BVI readers, TVIs, and access technology specialists, and underwent a rigorous evaluation with BVI readers [135, 112]. Key factors influencing our choice of T3 included its commercial availability, reliable and bug-free operation, and a comprehensive range of interactions. This allowed us to concentrate on assessing the integration of audio-tactile graphics into existing transcription and instructional workflows, rather than focusing on usability aspects of the interface, which were outside the purview of our user study. The T3 therefore served as a robust platform for conducting participatory research focusing on the utilization (rather than design) of audio-tactile graphics.

The user study included TVIs, tactile graphic artists, access technology specialists, and para-educators. During the design workshops, participants designed audio-tactile graphics on the T3 tablet following a design process we tailored specifically for this workshop. We refer to this process as the T3 Task Flow (T3TF) (see Fig. 4.2) to produce the audio-tactile graphics. The T3TF is an extension of the steps that tactile artists take to design tactile graphics.

In this paper, we present our findings from the two user study sessions at local intermediate school district offices, and summarize them in three broad areas

- A workflow for producing audio-tactile graphics in schools that builds on the existing tactile graphics transcription workflow
- Designs that enable the T3 to function as a guided exploration tool, allowing novice readers to independently navigate tactile graphics.
- Ideal scenarios in which audio-tactile graphics support educators.

Based on our findings, we expand upon existing design guidelines for audio-tactile graphics and discuss ways in which audio-tactile graphics can impact how educators and students currently access graphical information, including new transcription workflows and new pedagogies.

4.2 Related Work

Tactile graphics become highly interactive when they are paired with complementing audio labels. Audio labels have been known to increase the amount of information that can be presented through labels while avoiding clutter, in comparison to braille labeled tactile graphics [15]. Previous work has demonstrated various interactions for accessing audio labels on tactile graphics, such as using cameras mounted on the reader's fingers [189, 143] or overlooking their hands [65] as they read tactile graphics, through multi-touch display augmented with haptic feedback [75] , and through the use of tactile overlays on tablets [133, 111, 116, 126],. In this research, we focus our review on the body of work discussing audio-tactile interfaces involving tactile overlays for tablets which describe devices such as the T3 tablet. We draw our study design from previous studies involving experts and stakeholders in the design of assistive technologies. In the last section, we describe the steps involved in the T3 Task Flow.

4.2.1 Audio-labeled Tactile Overlays

Our research expands upon the design guidelines that were recommended and discussed in HCI literature on audio supported overlays for tactile graphic. Previous research on audio supported tactile overlay systems such as Miele et al's TMAP [135], Melfi et al's TPad [133] and Li et al's HTML Editor tool [116] all use a touch sensitive tablets with tactile overlays. Tablets enable readers to query for audio-labels immediately within the tactile overlay and other complex actions like editing spatial layouts and editing audio labels [116]. All of the systems mentioned here organize information across hierarchical layers of audio-labels in a manner that readers may query again at the same location to access additional details embedded in subsequent layers.

A widely discussed advantage of using audio labels is their benefit in reducing tactile clutter by avoiding the need to add braille labels while still retaining rich textual information [116, 133, 135]. We know from prior research that classroom teachers and students find it challenging to use braille labels when they extend across a graphic or overlapped tactile textures on a graphic [180, 7]. Audio-tactile graphics are therefore known to reduce tactile clutter while retaining rich detailed labels.

When presenting information through the combination of audio and tactile modalities, it is important that the audio information complements the perception of tactile details. Pandey et al discuss the importance of making important audio-labels discoverable and a unique exploration strategy that is afforded due to the flexibility of having both braille and audio-labels [148]. Siu et al found that audio labels are effective in providing both contextual annotations and details on demand, but ineffective at providing navigation cues to direct a reader's attention towards a different part of a tactile graphic [189]. Designers of audio-tactile graphics must carefully construct this interplay between audio labels and tactile features to support easy interpretation of graphics.

It should be noted that while previous studies provide a rich set of design guidelines that are foundational to our audio-tactile graphics, these guidelines emerge from the studies that evaluate usability from the perspectives of BVI readers. In a school context, educators would be responsible for the design of audio-tactile graphics, their use in classrooms and training students to read them effectively. Yet we know very little about their perspective on ways to design and use audio-tactile graphics. We know from pior work that educators such as TVIs and Tactile artists are important stakeholders in long-term adoption of audio-tactile graphics because traditionally they are often responsible for designing tactile images for BVI students and for teaching their students how to read tactile graphics [122]. Through our study, we explore how audio-tactile graphics can meet the needs of educators while also being usable for students. By designing audio-tactile graphics at our participants' workplaces, we aim to understand how our participants would design an audio-tactile graphics based on their current experience with tactile graphics and what factors influence the use of such graphics in classrooms?

4.2.2 Participatory Design of Assistive Technologies

Designers often use participatory studies that involve a diverse set of stakeholders to work on a collective task or problem statement as experts of their experiences [209, 163]. Participatory methods such as design workshops, co-design and field studies are often used in exploratory research because they allow researchers to gather perspectives of a diverse set of practitioners surrounding the use of an existing or novel access technology[122, 126, 116, 4, 37, 86]. Some examples of such stakeholders of access technologies from the cited studies include - occupational therapists, industry designers and end-users, and were aimed towards designing novel access technologies to be used by people with disabilities in day-to-day tasks. Prior research recommends ways in which design workshops can help explore strategies for instruction that complement the use of assistive technology in collaboration with educators. For instance: Stangl et al's workshop with sighted educators and BVI students discussed how instruction that complements access to tactile media is critical in students' ability to develop tactile literacy over time [194].Shi et al's goal with their co-design was to a)design interactive 3D tactile models in collaboration with BVI students and their teachers, and b) develop a teaching plan that complemented the designed graphic [181]. Hu explored new paradigms of designing tactile graphics through co-design with TVIs and visually impaired students, and contributed specific instruction-relevant design considerations to make graphs accessible and also compatible with TVI pedagogies [90].

To summarize, participatory approaches like co-design workshops have traditionally been used when studying complex ecosystems surrounding the use of access technologies. Our study did not involve BVI student participants. Our focus is on the design decisions that guide educators when they design audio-tactile graphics. Through the design workshop task in our user study, we study the new collaborative workflow our participants follow for producing audio-tactile graphics on the T3. We follow the example of Matuk et al who recommend involving teachers closely in the process of designing educational tools, as this helps to establish accurate design requirements and more closely addresses teacher and student needs because the teachers can *contribute their professional expertise to shape the tools of their practice, and ultimately ensure their sustained use*[130].

Additionally, we are also interested in learning about teaching strategies that involve using T3 in classrooms. audio-tactile graphics at our participants show that access to tactile graphics alone isn't sufficient, and it is important to use a pedagogy that complements the use of tactile graphics. [218, 126]. We know that BVI students require prolonged exploration of tactile 2D and 3D representations, accompanied with continuous feedback in the form of physical and verbal cues from TVIs, to develop an understanding of tactile graphics and read the encoded details in various 2D and 3D images [14, 66]. By exclusively inviting educators as participants in our study, we were able to learn how they imagined using an audio-tactile graphics tool - the T3 audio-tactile tablet, in a classroom setting. In a follow-up long-term field deployment study involving T3 the authors focus on the effectiveness of the resulting audio-tactile graphic and complementary teaching strategies that our participants discussed in this workshop.

4.2.3 T3 Task Flow

The translation task flow discussed by Ladner et al. visualizes the typical steps taken when transcribing a visual graphic into a tactile graphic [111]. These steps include tracing the image, developing a key, adding labels, and printing the tactile graphic using a suitable method.

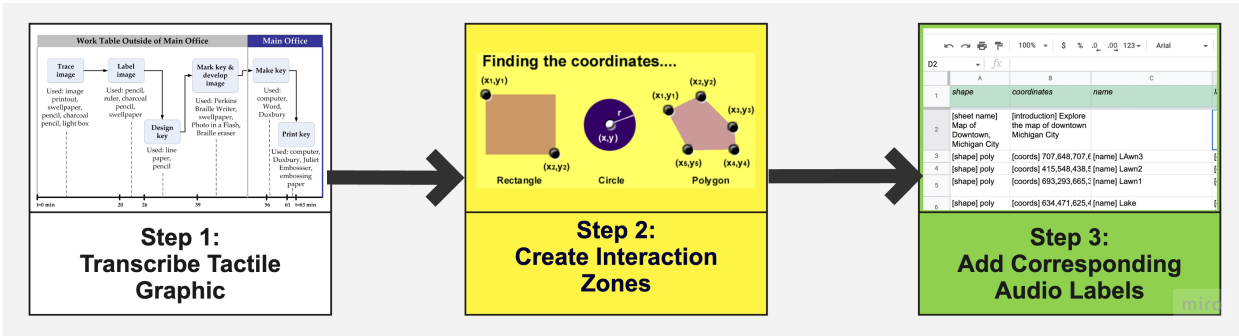


Figure 4.2: T3TF workflow. Step 1(left): Transcribing a tactile graphic for the overlay following steps described in the TTF [111], Step 2(center): Create Interaction zones, Step 3(right): Add audio labels for the created interaction zones

During the workshop, we followed an ad-hoc process which expanded upon Ladner et al's TTF when designing audio-tactile graphics for the T3. We refer to this ad-hoc transcription process as T3 Task Flow. T3 Task Flow (T3TF) consisted of the following steps :

- **Transcribing the image into a tactile graphic**: Participants collectively mocked up a sketch of how they would design the tactile overlay. This image was then printed on a 11 inch x 11.5 inch swell paper sheet. The process of creating this tactile overlay mirrored the steps in Ladner et al's TTF.[111]

- **Creating interaction zones**: Any tactile feature that was designed to function as a location to query for audio label was treated as an interaction zone. Similar to HTML image maps [115], we generated the coordinates of the interaction zones for query-able tactile features. Each zone is denoted by a set of coordinates that form the outline of the interaction zone.

- **Assigning audio-labels to interaction zones**: Participants wrote the audio-labels for all interaction zones in the online database associated with the graphic. The database also supported different layering audio labels across multiple levels.

During the design workshop component of our task-based user study, participants performed majority of tasks in the Step 1 of T3TF by sketching the mock-up of the tactile overlay. Depending on whether one of the participants was a tactile artist, either a participant or one of the researchers created a tactile overlay on PIAF (Print in A Flash) swell papers using the mock-up. Swell papers sheets “swell” on the surface along printed patterns through a heat treatment process and are often used to create tactile graphics. Step 2 was executed by a member of the research team alone. Step 3 was performed collaboratively by the participants and the supporting research team member. This division of steps allowed us to situate the tactile overlay design decisions (step 1) in our participants' current workflow and expertise in designing tactile graphics. Steps 2 and 3 are unique to the T3 task flow and therefore required additional steps beyond traditional tactile graphics

4.3 Methods

We conducted two user-study sessions with participants who worked as TVIs (teachers of visually impaired students), tactile graphic designers, paraeducators, and access technology specialists. The goal of the user study was to understand how our participants would design T3 based graphics in a way that is compatible with their current practices. Participants were provided with DIY prototyping material such as sharpies, highlighters, wikki stix (wax coated woolen yarn sticks), draftsman (tactile sketching boards) and braille labelers.The workshops were organized at Intermediate School District (ISD) offices, where the participants typically worked and produced tactile graphics. Our choice of location for the design workshops allowed participants to use the design and production tools they typically used, as well as allowing us to situate our discussion within the context of their workplace. The workshop was followed by a focus group session during which participants discussed how they see performing these steps (excluding the ones performed by the research team) in their current jobs, and how they anticipate teaching concepts using a T3. The workshop setting enabled the researchers to encourage participants to leverage their expertise in tactile graphics and create an audio-tactile version while discussing their design decisions. Each session ran for 2 hours.

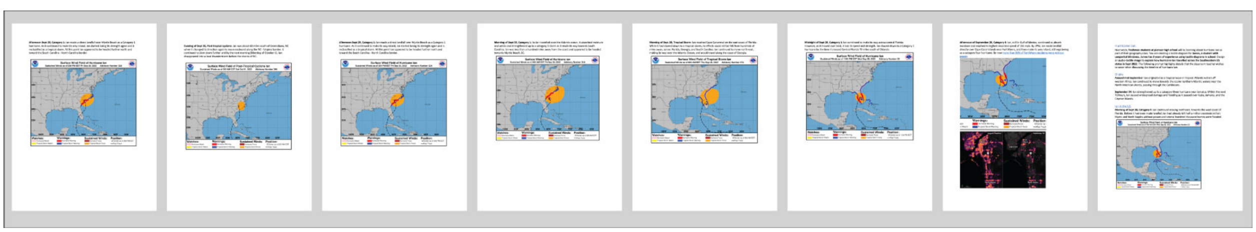


Figure 4.3: Design workshop prompt discussing hurricane Ian. We provided a series of screenshots from the NOAA website which depict the eye of the hurricane, hurricane wind forces, times and dates. There is accompanying text that discusses information which is relevant for each location of the hurricane.

4.3.1 Design Prompt

We asked our participant to design an audio-tactile graphic for James - a high-school student who is congenitally blind and has been reading tactile graphics in the classroom since elementary school. In the prompt (ref Appendix B), his teachers describe him to be comfortable at reading braille and tactile graphics independently. We aimed our design towards a more experienced reader in this generative design study because it allows for a relative ease of applying standardized guidelines during design, without many assumptions to be made about personalizing the design to the specific needs of the reader. TVIs often create tactile graphics for recent geographical events which are discussed in class. Our workshop prompt was about the onset of hurricane Ian in the Caribbeans US south-eastern states between 28 September 2022 and 30 September 2022 (see fig :4.3). Hurricane path maps are time series plots that indicate details about the hurricane over its course, such as - category of the hurricane, size of hurricane effect winds, location of the eye of the hurricane at various times during the storm. Hurricane path maps offer unique opportunities to combine and represent an event that took place over a course of time and superimposed on a more physical representation of a geographical map. We know from prior research that audio-tactile graphics favor complex detail rich graphics that otherwise have large amounts of text either overlaid or as a separate transcribers note. Therefore, the hurricane Ian path map was a detail-rich and text heavy graphic - making it ideal for presenting as an audio-tactile graphic.

4.3.2 Participants

The research team contacted local school districts that were known to provide vision impairment related special education services. Professionals who designed or taught using tactile graphics as part of their job were encouraged to participate in the user study. We selected participants who worked together on a team to attend the same session. This approach built on their current collaborations as a backdrop to situate their discussion about working with the T3. After an initial meeting discussing the workshop, 4 participants were short listed for each workshop session. P1-P4 were part of the first session, and P5-P8 were in the second session.

Three members of the research team were present during the study sessions to facilitate and assist our participants. Participants were compensated in combination of work credit hours and cash for their participation.

Figure 4.4: Participants in the first co-design workshop explore multiple methods for representing hurricane wind intensities and related data in tactile graphics. One approach highlights wind force through varying textures, while another emphasizes the sequential data along the hurricane's trajectory without the wind intensity depiction.

4.3.3 Data Collection and Analysis

After gaining participant consent for it, the workshop was audio and video recorded. The research team also recorded observation notes during the user study. The research team first went through the video recording and added to the observation notes. The designed audio-tactile graphics were analyzed using multiple data sources - combined observation notes, recorded conversations, similarities to the BANA guidelines[29], and participants' mock-up sketches. We used thematic analysis to then analyze all the collected data, i.e - recorded conversations, combined observation notes, and designed audio-tactile graphics. This enabled us to build up themes as we went through the data. One researcher coded and identified themes that emerged from one workshop. The research team then discussed these themes to refine the codes. The lead researcher then coded the second workshop using the refined set of codes. The quotes presented in this paper are lightly modified to account for interruptions that resulted from two participants speaking at once, or distractions from the audio announcements from the device. We have also redacted any identifiable information from quotes.

Table 4.1: Study 2 Participant List and Job Description

Workshop Session #	Participant #	Job Description
#1	P1	TVI
#1	P2	TVI
#1	P3	Paraeducator
#1	P4	Tactile Graphic Artist
#2	P5	Itinerant Services Director
#2	P6	TVI
#2	P7	TVI
#2	P8	Access Technology Specialist

4.4 Findings

In this section we discuss our findings from both user study sessions. We organized our findings in the order of their contribution towards our research question. First, we discuss how our participants approached the design of audio-tactile graphics on T3 and the factors they considered as part of their design process(RQ1) under a) Opportunities to Empower Novice Readers Using Audio-Tactile Graphics and b)Scenarios for using audio tactile graphics in classrooms.

Next, we present what we learned about the factors that would influence our participants' design workflow when using T3 (RQ2) under c) Insights on audio-tactile graphic design workflow in schools.

4.4.1 Opportunities to Empower Novice Readers Using Audio-Tactile Graphics

Participants from both sessions explored the various affordances of the T3, noting its support for students in independently navigating tactile graphics. In this section, we unpack participant comments about the attributes that made the audio-tactile graphics on T3 more suitable for independent learning, and the design decisions which could enable this independence.

4.4.1.1 Audio-Labels Eliminate Disorienting Hand Movements Between a Diagram and Key For Novice Readers

In tactile graphics which contain a key, readers must move their hands between the tactile diagram and it's key in order to understand the encoded information. Our prompt for

Figure 4.5: Photos and scans of the mock-ups that participants sketched for the hurricane Ian path map from the first (top and bottom-left) and the second (bottom-left) co-design workshop.

the hurricane Ian map also contained a key in it's visual image. The back-and-forth hand movement meant that the reader had to re-orient themselves within the tactile graphic every time they moved their hands away from the image. TVI participants explained that they often assisted their students in re-orienting within the diagram. Our prompt for the hurricane Ian map also contained a key in its visual image. Our participants chose to label the audio-tactile diagram such that the information which would otherwise be presented in

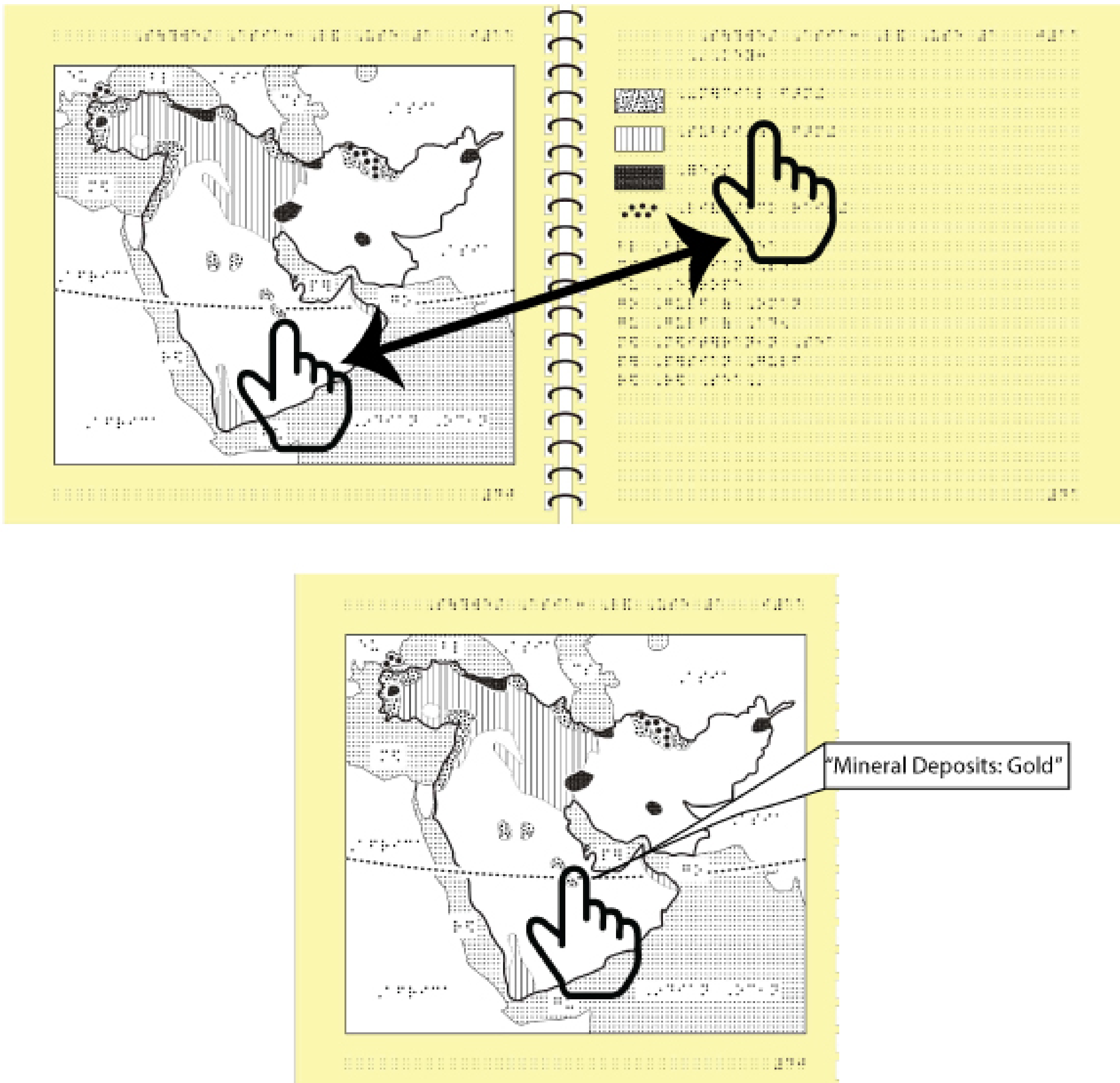


Figure 4.6: Back and forth hand motion readers have to perform to refer to the key in tactile graphics (top). In comparison, audio-tactile graphics allow users to query for key-related information from within the graphic without moving their finger away.

a key was embedded as an audio label. Participants advocated this audio label configuration could potentially reduce TVI intervention as it minimizes the need for students to move their hands away from a tactile diagram (fig 4.6).

Pre-teaching is a process in which TVIs introduce a tactile graphic to the student by walking them through the parts of a graphic. This is important because it helps familiarize students to the tactile graphic before they use it in a classroom setting where their general-education teacher teaches them subject-matter referring to the graphic.

> *"Researcher- Do your students typically read tactile graphics independently during pre-teaching?*
>
> *[P6]- no the audio would have a big part of that you'd (the T3) be doing what we are doing, which is reading with them to tell them where they're at when they have to go back and forth between the key and map. That's where the audio part is important."*

Here, P6 explained that a student would often need help re-orienting within a diagram when they left their position, especially to look at the key. It is clear from their observations that the T3 affords a new exploration procedure for tactile graphics which is different from the way students currently read tactile graphics. P6 viewed this new exploration process as a way to better support students in reading graphics more independently.

4.4.1.2 Opportunity to Improve Reading Accuracy

Braille labels on tactile graphics are often constrained spatially due to other tactile features. This is an inherent limitation since tactile graphics present both - the image and its labels in the same (tactile) modality. A widely known benefit of audio labels is that they can be co-located with tactile patterns and features without being a distraction. For our participants, this indicated that audio labels could be linked more precisely to a tactile element compared to braille labels, which typically rely on interpreting their proximity to an adjacent element. They viewed this as a method to enhance the accuracy of graphic reading and to offer more queryable elements, thereby aiding novice readers in accurately interpreting the entire tactile graphic. For instance, the image in our prompt did not contain labels for the states, but P4 chose to label the states in the audio layer because:

> *"[P4] If you are touching Florida and you wanna know if this shape is Florida, then you get to know the exact name. So that's kind of a nice feedback."*

P4 chose to add the additional labels because they determined that this would support a more accurate interpretation of the graphic.

4.4.1.3 Hierarchical Labeling Supports Both Both Skimming Through and In-depth Exploration

When labeling the hurricane Ian path map, our participants were responsible for organizing information for each interaction point across various layers of audio labels. Participants described their criteria for organizing information, their main aim being to support quick scanning of major details. One way participants believed this could be achieved was by placing important hurricane details such as wind speed, direction of wind, hurricane category, date, and time - in the first layer of an audio label. Secondary details such as damage updates, NOAA warnings, power outages etc were placed within the second layer. Additional explanations of concepts (such as explaining what a gulf is and what an island is) were encoded in subsequent layers of relevant audio labels. When discussing whether they could reuse this tactile graphic for other tasks and lessons, participants discussed how their design choices can help promote reuse:

> *"[P8] so yeah you start here and add more levels of details (signing a layer-like motion with these hands). So the way older kids can go into further details... [P6] yeah, so then on the first layer for a third grade kid you can just say this is land... this is water (instead of 'this is the Atlantic Ocean' and 'these are the US states'). We can bring it down to that basic and have the option to go that deep."*

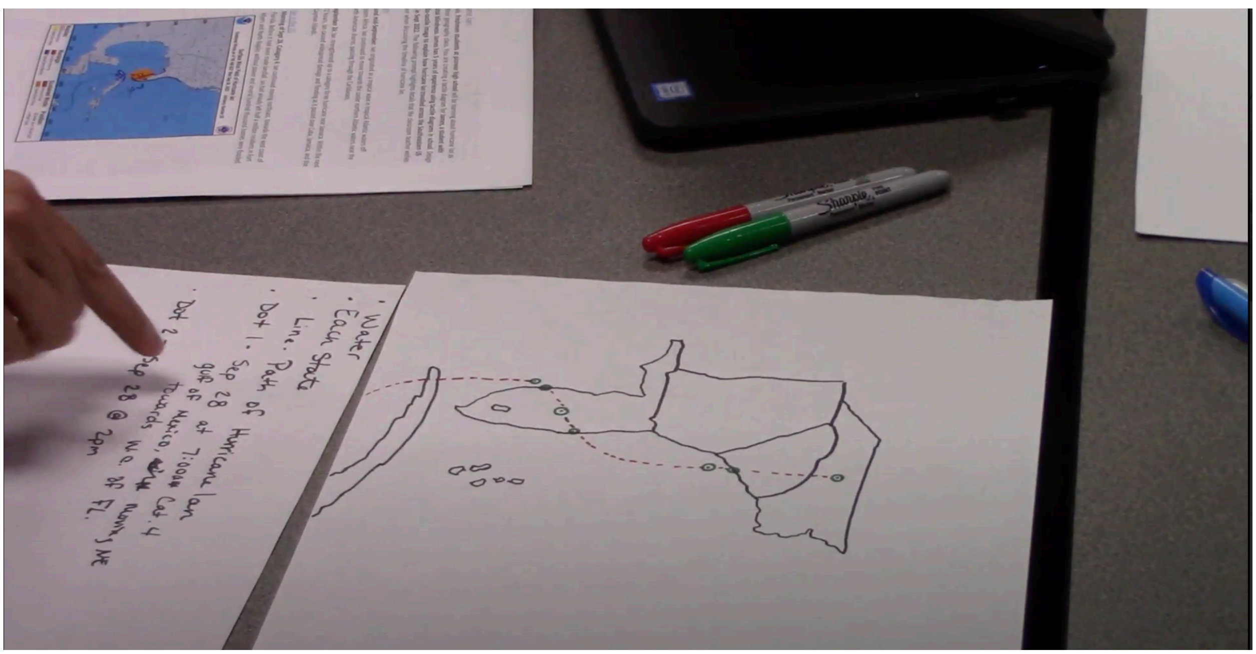


Figure 4.7: Photo of P6's worksheet in which they list how they would distribute hurricane-related information across different layers for audio labels that promotes easy skimming.

Here, participants discussed how the level of detail can vary based on the expertise or prior knowledge of the reader. Participants in the first session also described a similar hierarchy for labels, based on the 'relevance' of certain information within a given task context using the audio tactile graphic:

> *"[P1]My middle schooler, she would dig having [layered audio labels] because that information, it's more immediate instead of having to read through a long text ... I'm just looking for how many miles per hour the wind was.. so you know she can hit the button twice and there you have that info and it's there... [P2] this speed [of accessing information immediately] would be important for her to keep up with the rest of the class".*

The goal of this hierarchy was to promote easy skimming through the information than is afforded by braille labels and text, and subsequently improve the speed of reading tactile graphics among BVI students so they can 'keep up' with other sighted and visually impaired students in the class.

To summarize, participants emphasized the effectiveness of audio-tactile graphics in teaching students with elementary tactile literacy. Key benefits identified include the accurate alignment with tactile elements, reduction of disorienting hand movements, and the ability to arrange audio labels to suit various exploration methods. These attributes could significantly enhance graphic reading and potentially lessen the necessity for TVI intervention during the pre-teaching activity.

4.4.2 When To Use Or Not Use Audio-Tactile Graphics in Classrooms

During their discussions, participants identified several factors that would guide their decision about whether to use the T3 or to present information as a traditional tactile graphic. Our analysis of their discussion outlines the following scenarios in which it would be more suitable to use audio-tactile graphics presented via the T3. In particular, they drew attention to a) The ideal lead time for audio-tactile graphics, and b) The level of complexity of the graphic.

4.4.2.1 Audio-Tactile Graphics May Require Longer Lead Time

We know that when designing an audio-tactile graphic, we have to first design the tactile graphic overlay and then add detailed audio labels to it. Creating audio-tactile graphics therefore takes longer than tactile graphics. This is a critical constraint to consider in an educational setting where teachers are often expected to design graphics at short notice:

"[P8] teaching is so time consuming already…[P6] and we have to act so fast and then by the time you whip up something as complicated like this, they would have already gone on to the next topic"

Audio-tactile graphics would need a longer lead time to produce than traditional tactile graphics and are therefore more suitable when TVIs receive the images to be transcribed well in advance of a classroom lesson. This means that audio-tactiles are also suitable for graphics that would be used more than once since educators preferred to use simpler materials when a tactile image is to be used only once:

"[P7]for some of the orientation and mobility (O&M) graphs that I make just for that one room, I just use velcro and that's easy enough because I can make it by hand[…] [for O&M graphics] something like this would be just an overkill"

4.4.2.2 Detail and Complexity in a Graphic

Often, when studying concepts that involve complex images, students will refer back to the graphics during revision sessions. Our participants unanimously agreed that the T3 would be most suitable for graphics that present a level of complexity that would typically require a student to spend time studying it after class. P6 discussed a scenario with one of their students in mind, imagining how they might use the T3 in a review session:

"[P6]- Usually they will have a room where they have all their braille equipment. So now they would be able to review all this. That's where I see this(T3) would come in[…] With this one kid I had, she was gifted! We would sit with her in class and listen to the lecture, then we would go have our own tutorial about what the teacher said[…] This takes time, for all of this it just takes more time. And then you have to have that other review session if you want her to know how to read a map, and how to track a hurricane on a tactile map, we must spend time on that and she's going to need some time to learn all that in a different setting."

In a previous discussion, our participants noted ways in which audio labels could provide scaffolding during independent exploration of tactile graphics. P1 recognized that audio-tactile graphics could support students during independent revision. These graphics scaffold some of the tasks that would otherwise require support from a paraeducator or TVI. During our focus group discussion about how our participants imagined their student using the designed graphic, P1 said:

"The way that I see a student using this graphic is not in a classroom setting, but in a tutorial setting almost, where he is listening to the lecture and then now he

is in a quiet space.[...]So with this, he will be like 'okay so teacher said all this, let me go back to this tactile and look at all this' [...] You know thats where this would come in handy. Because otherwise as a middle schooler, he would need a para educator sitting with him going over all this."

For P1, the interactivity afforded by an audio-tactile graphic on T3 was a form of *"reinforcement"* for students that would encourage them to read the graphic on their own. They imagined T3 to be useful in supporting easier interpretation of a graphic, therefore reducing the level of intervention required from a paraeducator during the *'tutorial'* session. We observed that while audio-tactile graphics offer a range of benefits over traditional tactile graphics, they are in no way a replacement for tactile graphics. Rather audio-tactile graphics are suitable for specific use-cases in an educational setting, depending on factors such as available time, the complexity of the graphic and individual teaching strategies. In the next section we discuss design approaches to audio-tactile graphics that leverage their strengths and are compatible with the existing workflow for creating and teaching using tactile graphics in schools.

4.4.3 Design Workflows Differ for Tactile and Audio-Tactile Graphics

The design process for audio-tactile graphics differs from that of tactile graphics. Therefore, the workflows and job roles of educators would change when working with audio-tactile graphics. Beyond the obvious differences in the steps involved in producing audio-tactile graphics, we identified two unique steps in audio-tactile transcription process that would impact the jobs of educators:

4.4.3.1 Responsibility for Adding Elaborate Audio-Labels

Labels on tactile graphics can sometimes make the graphic itself cluttered. This is because a reader must differentiate between tactile patterns and braille text. Designing complex tactile graphics with large amounts of information is challenging, because *"too much detail in a tactile graphic can make it overwhelming"*(P2). Designers, therefore, are often responsible to go through the details of an image as they transcribe it and prioritize including essential information rather than all information [29]. From prior studies we know that audio labels improve this process because they accommodate larger amounts of information [133], and designers can include more details. During our design workshop, our participants discussed how they could include more detailed in audio-labels than braille labels, and how they would organize that information across different layers (fig: 4.8).

"[P7]- It's like trying to tell a story but over multiple days and it's all in one image ...This would add more depth to labeling, because it's almost like teaching, what a classroom teacher would do"

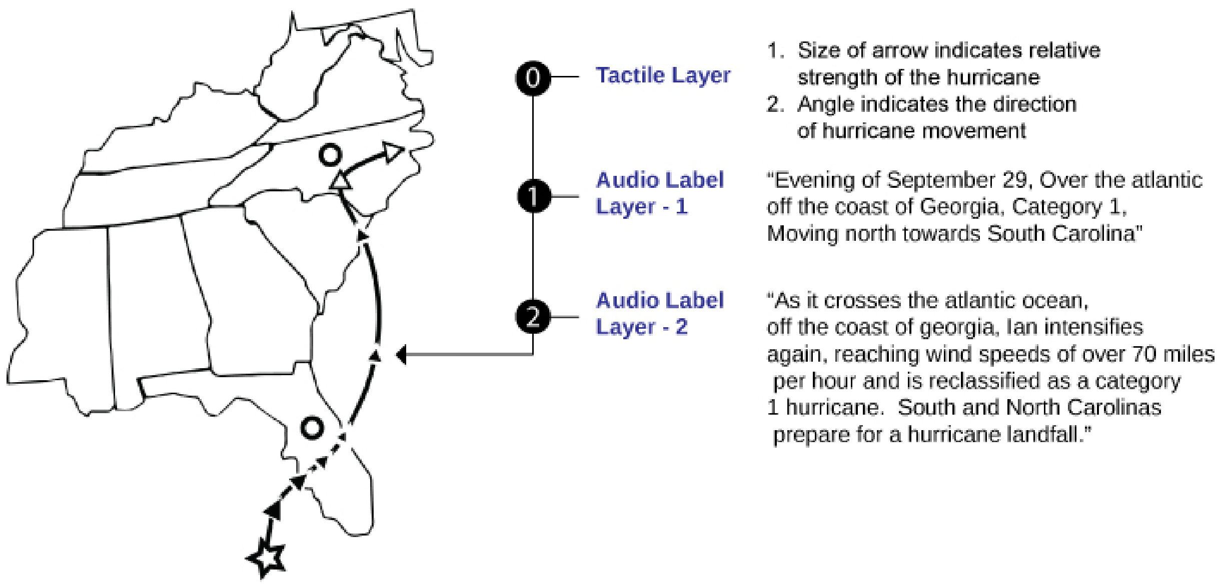


Figure 4.8: Hurricane Ian path map designed during the first design workshop. Participants distributed the information between the tactile layer and 2 hierarchical audio labels. This information would otherwise all be encoded in the tactile patterns and braille text if it were presented as a tactile graphic.

However, participants also noted that the opportunity to add descriptive audio labels meant that labeling would now become a significantly more time consuming task in transcription. Our participants recognized that this could change their job role:

"[P6]-I like the concept of it, but it just sounds like a ton of work ...you wouldn't have time to look up and provide content that would go in on all data points, that would be too much... that needs to come from the geography teacher you know? because I would just be on google looking it up... i would quit my job."

All participants who worked as TVIs (P1-2, P6-7) reported that their current workflows lack clear definition of who is responsible for adding labels to audio-tactile graphics. Our participants viewed labeling audio-tactile information as a task more closely linked to teaching than labeling in tactile graphics which was the responsibility of a tactile artist. Participants discussed how layering detailed audio-labels would require the subject matter expertise which a paraeducator or a classroom teacher are more likely to possess.

4.4.3.2 Current and New Pedagogies Involving T3 Graphics

A student's ability to read tactile graphics is a prerequisite skill to their ability to understand concepts that are explained using that graphic [134]. Prior studies point out how the lack of exposure to complex tactile graphics affects a student's ability to understand tactile graphics, and how this becomes a barrier that prevents many blind students from learning STEM subjects [111]. Our participants imagined using audio-tactile graphics to scaffold a student's ability to interpret tactile graphics independently (discussed in Finding 4.1). One of the ways in which they imagined achieving this was through the use of descriptive audio-labels that. When designing their graphics based on the design prompt, P6-8 discussed ways in which they could use story-like audio labels to support easy interpretation of the abstract tactile patterns:

> *"[P6]- put a timeline out here, so it started here, [P8] - it went a hundred miles the next day, [P7]- yeah like it went from here to here in one day, and then you can relate that to what they know like how long would that take in a car for you to go from your house to school [...]The speed, and distance covered that can be announced at first. And if the student is ready for more you would talk about all the other detail in the second level (of audio label) - how did it pick up speed? Why did it slow down over land? Explain that it's like bumping into things with your cane, and that way you can make it relatable to the blind student."*

In this quote, P7 describes the information they would add to an audio label to explain the abstract concept of a hurricane slowing down over land, comparing it to a students' cane touching objects in their surroundings, thus slowing them down. Descriptive story-like labels which could make information encoded in the tactile graphics *"relatable"* to the blind student were seen as an opportunity to off-load some of the instruction onto audio labels. These decisions would require a closer collaboration between tactile artists, TVIs and classroom teachers who would be teaching concepts referring to the audio-tactile graphic. The step of adding details to audio labels blurred the boundary between creating a graphic and teaching using the graphic. Current workflows for designing tactile graphics have these steps more clearly distributed between TVIs and classroom teachers. In the discussion below, we further address how it is critical to consider these discrepancies between the design workflow for traditional tactile graphics and audio-tactile graphics in tandem with developing the technologies for delivering educational materials using this new approach.

Figure 4.9: P6 demonstrating the story-like audio labels to allow for a sequential exploration of the hurricane Ian tactile graphic. Here P6 is demonstrating their organization of hierarchical audio labels.

4.5 Revisiting Recommended Guidelines

In the preceding sections, we have reviewed prior research on audio-tactile graphics to summarize a preliminary set of design recommendations that have been evaluated by visually impaired readers. These guidelines allow authors to add audio labels that complement tactile exploration and assist users when interpreting the encoded information in the tactile overlay. In this study, we have learned about ways in which educators would approach the design of audio-tactile graphics using their prior experience making tactile graphics, in a manner that can potentially be carried out in an educational environment. Based on our findings, the following three design considerations serve as points of departure for thinking about the design and use of audio-tactile graphics in education:

4.5.1 Explain content of the graphic as an introduction

We recommend providing an audio overview of the graphic as a short summary that can be accessed before a reader begins exploring the graphic. The goal of this summary is to 'familiarize' a reader with the graphic and its important features, contextualizing the encoded information before they begin exploring the tactile graphic by touch. By default, T3 supports this functionality via an introductory summary that is spoken when a new sheet is placed on the tablet. During our workshop, for example, P5 and P6 explained that for the hurricane Ian graphic:

> *"the starting announcement would be just to familiarize the reader with whats in the graphic. So that way I would say the first thing it should say is familiarize yourself with these dates.. [P5]- if there was a summary statement saying this is the map of south east USA, there's this line marking it went from here to here or however many hundreds of miles in one day or however you wanted to explain it..[P6] you can explain it in the way that they can relate that to what they know like how long would it take them to go by car[...]"*

In addition, we recommend adding details about the features which are important to know when exploring the tactile graphic, such as - *'The beginning of the hurricane is marked with a star at the bottom of the graphic'*.

4.5.2 Write Audio Labels in a Manner That Complements Tactile Exploration

Audio labels can complement tactile exploration, and in some situations act to guide readers. The following three considerations emerged during our workshop that demonstrate how audio labels can complement tactile exploration: We recommend organizing audio labels in a way that promotes modes both for skimming through the graphic and for deeper study. Our participants achieved this by organizing the date and wind speed detail on layer 1, and describing events and specific detail for each point on layer 2 and beyond. For time series based graphics like that of the path of a hurricane, audio labels can describe where to look for the next marker. This should be described in reference to a reader's current location on the graphic. We recommend designing interaction zones that make it easy for a reader to orient themselves within a graphic. In our map, this meant creating interaction zones for the underlying states to help users orient within the map of south-east US, despite that information not being explicitly provided in the visual diagram.

4.5.3 Support the Reuse of a Tactile Overlay With Multiple Audio Label Configurations

We recommend that designers consider designing the tactile overlay in a manner that allows for reuse with multiple audio label configurations, depending on the student's abilities and the task to be supported. This approach would help to optimize the efficiency of the transcription process and ensure that the audio-tactile graphics are designed in a manner that is flexible and adaptable to the needs of teachers and students. For instance during our workshop, participant P3 suggested having both a study and a *"quiz"* version of labels, where the study labels would provide more contextual information to assist in learning.

> *[P1]- "can we add a question to quiz them on what they've just read?... Because if they could go through it all and it goes 'bing, that's the right answer', that would be a good form of reinforcement."*

4.6 Discussion

We conducted this study with the goal of understanding how educators who currently use tactile graphics, would design an audio-tactile graphic on the T3, if the steps involved were similar to the steps for making tactile graphics. Through our task-based user study, we learned that our participants' job roles would differ significantly depending on whether they are creating tactile or T3 graphics. Our participants imagined T3 graphics would be easier to explore independently for their students than braille labeled tactile graphics because of the convenience of accessing co-located audio labels on tactile surface. Finally, our participants also discussed scenarios when they would or would not use T3 graphics instead of tactile graphics. In this section we unpack the impact of using audio-tactile graphics in schools. We focus our discussion on the following three subsections: a)New transcription workflows and job roles, b)Collaboration between classroom teachers and TVIs, c)Supporting independent learning and d)Social aspects of working audio-tactile devices.

4.6.1 New T3 Transcription Workflow

Our ad-hoc method of transcribing T3 graphics, i.e. - the T3TF, required two additional steps beyond the steps of transcribing the tactile graphic itself - a) Adding interactions zones to tactile features, and b) Adding detailed audio labels. This implies that audio-tactile graphics would inherently take longer turnaround times than tactile graphics, and educators would be required to undergo training in designing audio-tactile graphics graphic. These issues are critical to consider since we know from prior studies that TVIs typically don't receive images with enough lead time to produce tactile graphics before class [7, 133]. We also know that TVIs often lack sufficient training with tools and access technologies [134, 14]. It is important that future research consider these among other barriers to adoption of audio-tactile graphics.

Further research is required to create authoring tools that educators can use to create audio-tactile graphics. Learning from prior knowledge and our findings, we recommend designers of authoring tools to consider how their tool a)adds to the time required to transcribe a tactile graphic and b)requires educators to learn a novel skill required to operate a new system.

4.6.2 Collaboration Between Classroom Teachers and TVIs

For tactile graphics with braille labels, just-in-time modifications can only be performed by TVIs or tactile artists. Classroom teachers are often not equipped with the appropriate tools and skills for modifying tactile graphics. Modifications or elaborations to braille labels therefore require a significant turn-around time. Previous studies show that classroom teachers rely on the paraeducators for several support tasks when using access technologies to teach their students, including when making in-time modifications to a graphic when teaching [199]. Rosenblum et al studied collaboration between various educators in classrooms and found that it was critical to have an *"effective collaboration with both general education science teachers and paraeducators"* to successfully support visually impaired students learning STEM subjects [172]. Metatla and Cullen highlight ways in which modern assistive technologies (such as tactile graphics, braille readers) which enable access to course content are not inclusive when it comes to classroom instruction and collaboration with sighted peers [134].

We observed that the process of authoring audio-tactile graphics would require distribution of tasks among classroom teachers, audio-tactile artists, and para educators. Unlike in braille labeled graphics where classroom teachers are often consulted by TVIs and tactile artists to understand intended task and takeaways from the graphics, classroom teachers could potentially contribute directly to the detailed audio-labels in audio-tactile graphics, in a manner that complements their intended classroom instruction plan.

P4, a tactile artist, explained that *"the conversation in class could change... they could be talking about different details at each spot"*. P4 saw using T3 as an opportunity to involve the classroom teacher when adding detailed audio labels.

Unlike modifying braille labels on traditional tactile graphics, audio-tactile graphics do not require specialized tools to edit audio-labels. Our participants saw this benefit to adding and editing audio labels made it easier for classroom teachers or subject matter experts would be able to perform instead of relying on a para-educator. Our participants saw this improvement as a first step towards making classroom instruction complement the graphics that is produced. We believe that audio-tactile graphics present an opportunity to bridge the gap between the job roles of classroom teachers and tactile graphic specialists and thereby improve the overall experience for students of using audio-tactile materials in classrooms. Furthermore, the accessibility of digital interfaces like a screen reader enabled computer can allow students to author or modify audio labels.

4.6.3 Independent Exploration

An emerging discussion during our workshops was about T3's support for students during independent learning. For our participants, the immediate response of T3 meant that students could read and interpret graphics independently. For TVIs, independence in reading graphics is an important learning goal and prior research recommendations encourage classroom technologies that support independent learning. Baker et al's interview study revealed that TVIs increasingly want self-contained assistive technologies that support independent exploration and learning [18]. Phutane et al, also noted that interactivity of a tactile material was one of the factors that educators considered when deciding whether to use it for creating tactile graphics [161] Our participants felt that digital tools, such as the T3 and are poised to make tactile graphic exploration more interactive, therefore increasing the independence of novice students in particular. While our study did not evaluate this claim, in our finding section we list the aspects of T3 that were seen to promote "independence". Future studies are needed to evaluate this hypothesis that audio-labeled tactile graphics would support independent exploration of a tactile graphic in school setting.

4.6.4 Social Implications of Using T3 in Classrooms

Prior research has demonstrated that there are social impacts associated with the use of any assistive technology. For example, research has found that students feel assistive technologies draw unwanted attention to their disability, so that they might have difficulty receiving help from their peers [17, 185]. Our participants noted that T3 was a large tablet that was a) difficult to carry between classes and b) could be difficult to hear in a noisy classroom setting. A smaller form-factor for the T3 tablet can make the device more portable and closer to the mainstream tablet devices that are commonly used by sighted and blind users (such as an iPad). However this means we compromise on the size of tactile overlay corresponding to the compact and portable tablet. Designers can weigh on the benefits of this compromise to consider future iterations of such technology.

For the second point, some participants suggested that it would be most ideal if students used T3 in their resource rooms when revising in a private setting. This might be counteractive to the larger objectives of inclusion through the use of assistive technology as using the T3 would mean inadvertently isolating BVI students from their sighted peers. Other participants also recommended using headphones when using the T3 in classroom. While it can block the background noise of a classroom to help the user focus on the audio-labels, it could introduce difficulties when listening to both the T3 and their peers when working in mixed ability groups [166, 148].

4.7 Summary of the Chapter

This chapter covers the second study in this dissertation about the task-based user study that included a design workshop and focus group sessions, that we conducted to collaboratively create audio-tactile graphics using the T3 tablet within a school setting, utilizing the tools at hand. Participants were educators with expertise in teaching visually impaired students and who had experience in crafting, adapting, and instructing with tactile graphics - all of which was part of the ad-hoc workflow we devised for transcribing audio-tactile graphics on the T3, and was referred to a T3 Task Flow. The aim of the study was to explore how educators accustomed to collaborating on tactile graphics would adapt their collective methods to the design and creation of audio-tactile graphics within their work environments. A research team member was on hand to guide them through the transcription workflow elements specific to audio-tactile graphics. Conversely, participants drew on their proficiency with tactile graphics to manage familiar tasks. Subsequent to the workshops, a focus group was convened to deliberate on the transcription process and the practicality of the produced audio-tactile graphics. In these sessions, participants collectively crafted an audio-tactile graphic based on a given scenario, utilizing their expertise in designing braille-embellished tactile graphics. They recognized that embracing audio-tactile graphics might necessitate a shift in their professional responsibilities as they currently stand in creating and teaching with braille-labeled tactile graphics. There was also an eagerness to investigate how audio-tactile graphics might more effectively meet educational objectives that traditional tactile graphics fall short of addressing. The limited scope of the user study, primarily involving educators, posed a challenge in confirming these advantages with BVI students directly. Nevertheless, the following chapter introduces a field study aimed at corroborating the educators' predicted educational benefits from the use of T3-based audio-tactile graphics in classroom environments.

CHAPTER 5

Audio-Tactile Graphics in Practice: A Field Deployment Study of the T3 Tablet in Classrooms. [1]

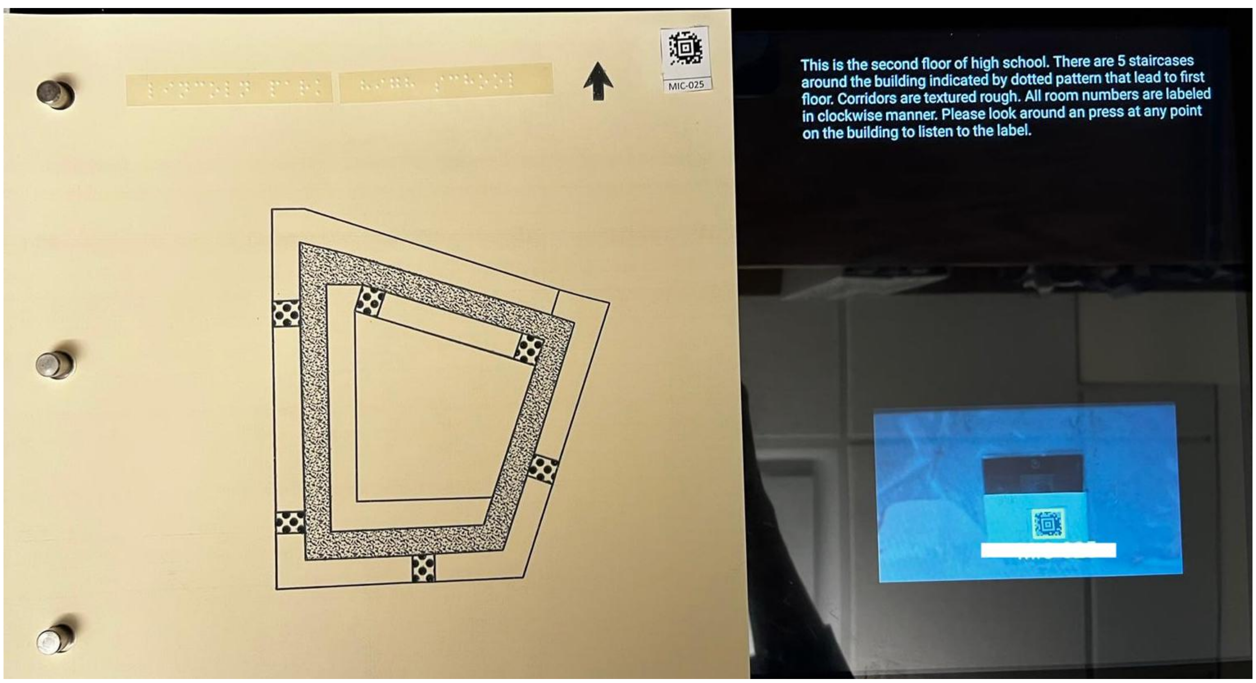


Figure 5.1: A PIAF based audio-tactile graphic of the floor map of second floor of the highschool. The graphic is placed on the T3 tablet. Introductory text that is announced when one places the graphic appears in print on the portion of the tablet screen that is visible next to the graphic.

[1] This chapter contains text that will be part of a submission to TOCHI 2024 proceedings

5.1 Introduction

Within the field of Human-Computer Interaction (HCI), there has been a growing interest in the accessibility of visual information for individuals who are blind or visually impaired. One modality that has received significant attention in this context is tactile graphics [122]. Tactile graphics are images that are conveyed as tactile patterns and braille text and are read through touch. Tactile graphics have been extensively studied for their ability to provide independence among students, support students in mixed-ability classrooms, and meet the pedagogical requirements TVIs when they teach using tactile graphics.

Typically, the information bandwidth and resolution of tactile graphics is lower than visual graphics because a finite number of textures available to encode numerous visual colors used in an image [27, 26, 29]. Additionally, the braille font size is standard unlike visual fonts that can be resized [28]. These constraints mean that designers often simplify visual images in the process of transcribing them into tactile graphics [29]. The loss of information during simplification can limit the effectiveness of tactile graphics in conveying complex visual information. To address this limitation, researchers have explored the use of audio supported tactile graphics, commonly referred to as audio-tactile graphics.

Audio-tactile graphics, which use audio announcements with tactile graphics to present visual information, have a larger information bandwidth than tactile graphics, having access to both audio and tactile modalities. However, in comparison to tactile graphics, audio-tactile graphics are relatively new and not prevalent in education. We lack a sufficient level of understanding about audio-tactile graphics relative to other classroom assistive technologies such as tactile graphics, which have been studied since the 1980s [55, 68, 110].

Design guidelines for tactile graphics that emerge from previous research have emphasized ways in which designers can use them to promote independence among BVI students[66], support the inclusion of BVI students in mixed-ability classrooms[134], and provide pedagogical support to classroom instructors [133]. However, we lack sufficient evidence to determine whether audio-tactile graphics could potentially promote independence among students, inclusion in mixed-ability classrooms, and the same level of pedagogical support to instructors as when they are teaching using tactile graphics. Here, ”pedagogy” refers to the instructional strategy for teaching both the skill of reading tactile graphics (as noted by participants in Study 2 and covered in Sec 4.4.3.2) and the delivery of course content using a given tactile graphic. To answer this question, we studied how audio-tactile graphics could meet the needs of educators and their BVI students within a classroom context over a period of 6 weeks. We also sought to understand how the preparation of audio-tactile graphics might fit into our participants’ current workflow for transcribing tactile graphics.

The T3 Tablet: During our field deployment study in schools, we employed the T3 audio-tactile graphics tablet (Fig. 1.3) as a modified version of the TMAP audio-tactile tablet. The TMAP device was developed in partnership with BVI readers, TVIs, and access technology specialists, and underwent a rigorous evaluation with BVI readers [135]. The T3 tablet comprises a tactile graphic overlaid on an Android tablet. The tactile overlay presents a part of the graphic in the form of tactile lines and patterns. The Android tablet announces textual details from the graphic that are associated to the tactile elements on the overlay. Users can interact with the T3 tablet through gestures that do not hinder the exploration of the tactile diagram. Specifically, the T3 tablet supports one-finger swipe gestures, similar to talkback screen reader interactions, to navigate menus for adjusting volume, speech rate, and accessing tutorials. Users can query for audio-labels by pressing down on the tactile element in the overlay. Upon placing the overlay sheet on the screen, the tablet automatically loads an audio-label file associated with the overlay. One can compare the exploration procedures involved in reading a T3 graphic to a combination of the hand movements required to read tactile graphics and the gestures executed on tablets or mobiles utilizing a screen reader. Additionally, T3 graphics can embed audio-labels in a hierarchical manner, with deeper labels being accessible by pressing upon the same location multiple times.

Through our study, we aim to answer the following research questions:

- **Understanding Initial Adoption**: How can educators incorporate T3 into their current instructional plans for students? What strategies do teachers use when teaching with T3?

- **Understanding Practical Audio-Tactile Graphic Designs**: What are some designs of audio-tactile graphics that support pedagogies in various contexts, such as classrooms, pre-teaching sessions, and homework assignments?

- **Understanding Whether T3 Graphics Support Educational Outcomes**: In what ways does T3 support, or not support, students and teachers in achieving their educational outcomes?

To answer these research questions, we studied how educators used the T3 to teach audio-tactile graphics with their students over a period of 6 weeks. We recorded our participants' experience using T3 based graphics with their students to understand how - teachers develop strategies for teaching using the T3, and how the students develop the skills to interpret and perform tasks using the audio-tactile graphics. Through this deployment study we contribute the following:

- An understanding of the design space for audio-tactile graphics in education to promote long-term adoption of audio-tactile graphics in education, including the pedagogies supported by audio-tactile graphics, needs of teachers and students during learning tasks, and education outcomes that are better supported by audio-tactile graphics than braille-labeled tactile graphics.

- a set of design guidelines for audio-tactile graphics that leverages the existing methods educators use to create tactile graphics with their current production tools. Our recommended guidelines ensure that educators can easily transfer their expertise to the creation of newer audio-tactile graphics.

- opportunities for inclusive instruction in mixed-ability settings through the utilization of audio-tactile graphics. Our findings show the T3 fosters collaboration between sighted and visually impaired students within classroom environments.

5.2 Related Work

5.2.1 Advantages of Audio-Tactile Graphics

According to Zebzay and Wilton, using tactile graphics along with a textual description about the image is the most effective way to present visual information to BVI students [218]. Prior research highlights benefits of using tactile graphics in fields like STEM education, data science, navigation, among others [219, 142, 100, 65]. In practice however, there are several design and practical limitations that affect the overall usability of tactile graphics. Tactile graphics are often limited in the amount of information they communicate compared to the visual graphics [34] because it can be challenging to include large amounts of tactile details and associated braille labels without designing overly complicated and cluttered tactile graphic [198]. Previous research discusses how educators tend to avoid using diagrams whenever possible and opt for descriptions instead due to the time-consuming nature of diagrams [179]. Additionally, students undergo regular training over time to learn how to read and interpret tactile graphics as part of their expanded core curriculum (ECC) in addition to regular classroom instruction [8, 119]. According to Sheppard and Aldrich, there are three major challenges commonly encountered in the production of tactile graphics: excessive labeling, difficulty in creating a meaningful representation when translated, and a time-intensive process for creating the image [179]. Previous research on audio-tactile graphics has sought to tackle some of the known design-related limitations with tactile graphics, such as improving the amount of information encoded in a graphic by offloading braille labels to audio-labels and making the resulting tactile overlay less cluttered [34, 133], and using descriptive audio labels to aid in the exploration and interpretation of the graphics [65, 148]. While such studies provide guidelines for designing audio-tactile graphics that are usable by BVI readers, we currently lack research concerning how the resulting graphics perform long-term when used in practical contexts, such as in a school setting. It is therefore unclear how audio-tactile graphics can address some of the practical limitations commonly encountered when using tactile graphics in the context of education, such as - the additional time that TVIs require to produce tactile graphics and additional training BVI students undergo to develop the skills required to read tactile graphics [9], the challenge of meeting the expected pace of reading as their sighted peers when reading the graphic in a classroom [161], and the level of assistance BVI students receive from classroom teachers and sighted classmates [16, 30].The aim of this study is to explore how audio-tactile graphics can support educators teaching classroom scenarios. We want to understand both the practical limitations and benefits of using audio-tactile graphics in schools, similar to what we already know about tactile graphics.

5.2.2 Designing Audio-Tactile Graphics.

Audio-tactile graphics have emerged as a popular alternative to traditional tactile graphics when presenting graphical information in an accessible manner. While there are various implementations of audio-tactile graphics, our review specifically focuses on systems that are similar to the T3, i.e. - those which utilize audio-augmented tactile overlays which users interact with through touch-based gestures.

Previous studies comparing tactile and audio-tactile graphics show improvements on a number of criteria when tactile graphics are accompanied with audio labels. In a study conducted by Melfi et al, participants who used the TPad audio-tactile tablet were able to explore a tactile graphic faster and demonstrated improved memorization of information compared to those who performed the same tasks on a tactile graphic [133]. Brock & Jouffrais observed that people with visual impairments could remember and mentally manipulate both route and survey spatial knowledge through the use of an audio-tactile map with the same accuracy as a tactile map with braille labels [33]. In another study, Brock et al compared audio-tactile and tactile maps of geographic relief features based on their efficacy, user satisfaction and effectiveness - measured in the form of spatial learning. They observed a significantly higher efficacy and user satisfaction for audio-tactile maps, but similar levels of effectiveness [34].

Previous research evaluating audio-tactile graphics from the perspective of BVI readers have provided valuable design recommendations. These recommendations emphasize the importance of ensuring that audio labels effectively complement tactile components by facilitating usable interactions. For example, Holloway et al. demonstrated that using audio labels instead of braille labels enhanced the usability of audio-tactile graphics for individuals who are unable to read braille. Additionally, audio labels provided more detailed information compared to braille labels. This was possible because audio labels could be included as layers in a hierarchical structure. This provided a sense of depth as users searched for information at different levels of an audio label. Unlike braille-labeled tactile graphics, designers could update the text for audio labels without having to reprint the tactile overlay.[88]. Pandey et al's study with audio-tactile graphics discussed how audio-labels can complement tactile exploration. They recommend making audio labels discoverable by using abbreviated braille labels tactile symbols. They also suggest providing an overview of all the audio labels in a graphic to give users a sense of what to expect. Additionally, they suggest using interaction gestures for querying labels that do not interfere with tactile diagram exploration gestures. [148].

Previous studies on audio-tactile graphics systems have mainly evaluated their use in laboratory or workshop settings, with a focus on visually impaired users[148, 88, 33]. A limitation of previous work is that they have not thoroughly explored the practical application of audio-tactile graphics in real-world scenarios, the workflow for producing audio-tactile graphics, or the impact on the utilization of these graphics in realistic contexts such as education. Additionally, the limited commercial availability of systems designed for presenting audio-tactile graphics has hindered their widespread use beyond research environments.

5.2.3 Factors Shaping Tactile Material Selection for TVIs

When studying the long-term use of assistive technologies by adults with visual impairments, researchers have examined various socio-technical factors that affect the initial adoption and ongoing use of the technology for both BVI readers and educators. These factors include ease of use, ease of instruction, cost, collaboration capabilities, user effort, cultural and social identity associated with the technology, product aesthetics, and confidence in the technology [30, 31, 99, 151, 185]. In the specific context of education, Baker et al. noted that previous research mostly focuses on device-centric factors that affect the adoption of assistive technology [16]. There is limited research on context-specific factors that also impact the adoption of assistive technology.

Baker et al [16] conducted interviews with TVIs to understand how they determine which assistive technologies to use with their students. They reported that the following factors influenced their decision: a) aligning with the technology utilized by sighted students, b) considering student-specific, environment-specific, and task-specific (S.E.T.) requirements (i.e. whether a tool is appropriate for a student's expertise, environment of use, and task at hand), and c)taking into account the student's preferences and expertise. According to Phutane et al [161], when TVIs consider using new tactile materials to create tactile graphics, they take into account the following factors related to their teaching workflow and educational goals: a) improvements to the amount of time spent teaching, b) student interest in the resulting graphic, c) improvement to student independence, d) whether student is able to match expected pace or the pace of sighted peers, and e) potential for reusing or re-purposing the graphic.

To summarize, Baker et al. and Phutane et al's research provides following qualitative factors that inform the long-term adoption of assistive technologies such as the T3 in educational settings:

- The time educators spent in teaching when using the novel assistive technology as compared to other alternatives
- Our participants' impression of how interested their students were in using the novel technology for learning tasks.
- A BVI student's ability to independently use the novel assistive technology as compared to other alternatives.
- Whether BVI students met the educators' expected pace of learning, or the pace of their sighted classmates.
- Whether the content on novel assistive technology could be potentially reused or repurposed for a different lesson or exercise.

5.2.4 T3 Graphics Workflow During Deployment

Throughout the deployment phase, a designated research team member, henceforth referred to as the 'T3 Graphic Artist', assumed responsibility for creating audio-tactile graphics tailored to our participants' specific needs. Our production approach followed an ad-hoc procedure referred to as the 'T3 Task Flow' (T3TF) for the design of these audio-tactile graphics. In our collaborative efforts, we prioritized aligning with our participants' weekly teaching schedules, ensuring a timely delivery of each audio-tactile graphic as per their instruction schedules with their students. As mentioned in previous study, T3TF comprised of three key steps:

- **Transcribing a tactile graphic overlay**: T3 Graphic artist would create a digital design of the tactile overlay, following the design guidelines that are commonly used for transcribing tactile graphics. The guidelines we followed are detailed in Appendix 5.7. After being previewed by our TVI participants for feedback, this design was printed on an 11 inch x 11.5 inch swell paper sheet. This process of creating the tactile graphic overlay mirrored the process outlined in Ladner et al's Tactile Task Flow. [111]

- **Creating AudioLabel-Query-Zones**: Any tactile feature that had an audio label associated with it had to be scripted as an interaction zone in a database associated with that graphic. The coordinates of the area associated with the tactile element served as an interaction zone, similar to HTML image maps [115]. Each interactive element on the tactile overlay was assigned a unique object name and a set of coordinates that formed an interaction zone where one could query for audio labels.

- **Assigning Audio-Labels to Interactive Tactile Elements**: The T3 artist created an initial list of audio labels associated with each tactile element, using the source image provided by the participant. This information was entered alongside the interaction zone details in the database in the form of a Google Spreadsheet document. Participants were given access to this document to add additional details and customize the spreadsheets as per their instruction strategy. Using the spreadsheet, one could add or edit introductory announcements and audio labels and embed additional audio labels as subsequent layers for any tactile element.

In the workflow for creating audio-tactile graphics during our deployment study, the role of the T3 Graphic Artist closely resembled that of a tactile graphic artist tasked with transcribing braille-labeled tactile graphics in educational settings. TVIs were given the liberty to enhance the tactile overlays that we produced for them through various DIY tactile add-ons (such as stickers, buttons and textured papers) and to personalize audio labels for the graphics in real-time, similar to their current practice of modifying tactile graphics, on-the-fly, as per their instructional and student needs.

5.3 Methods

During our 6-week long field deployment study, we equipped two participants with T3 tablets to be used as a tool for instruction with one of their students. The participants were granted the autonomy to employ the T3 devices in a manner that aligned optimally with their specific educational objectives, and alongside any other assistive technology they were already using with the student. As discussed in the previous section, throughout the deployment phase, a dedicated T3 Graphic Artist followed a workflow closely resembling that of a tactile graphic artist, when assisting the TVIs in producing audio-tactile graphics for their lessons. This workflow is illustrated in Figure 5.2. We strictly adhered to customary turnaround timelines, incorporating tactile markers and texture patterns as per the participants' preferences, and providing support for their established teaching methodologies.

Additionally, to support our participants in training their students on mastering the T3's gesture-based interactions, we provided them with copies of the T3 starter pack sheets generously provided by Touch Graphics [206]. An example starter pack sheet for a grocery store floor plan is depicted in Figure 5.8. These sheets also featured engaging games, simple maps and shape exercises that were meticulously designed to foster the development of exploration techniques essential for interpreting audio-tactile graphics.

5.3.1 Recruitment

In addition to contacting the TVI participants from Study 2, we reached out to other neighboring school districts known for providing specialized education services for students with visual impairments. TVIs who expressed interest in participating were then evaluated and shortlisted based on the following criteria:

- **TVI requirements**: The TVI participant should meet with their student at least once a week. They should be currently teaching using tactile graphics. They should commit to using the T3 during at least one lesson per week, and be available for check-in interviews with the research team. Additionally, they should submit a diary entry for each teaching session.

- **Student requirements**: To participate, the TVI should be working with a student who is in middle school or higher and has prior experience interacting with tablet or mobile based screen readers. Additionally, they should be comfortable using tactile graphics and are using them as part of their current curriculum at least once a week.

5.3.2 Participants

We worked with two participants during our deployment study.

Participant 1, also known as P1, was an itinerant TVI who worked with 18 students in various schools within their school district. For this study, P1 specifically worked with S1, a middle school student who has been visually impaired since birth. S1 has been using tactile graphics to learn subjects such as math, science, geography, and orientation and mobility (O&M) throughout their life.

Typically, P1 collaborated with a tactile graphic artist to create tactile graphics for various subjects. For this study, P1 utilized the T3 tablet to teach geography to S1, while still employing traditional teaching methods for other subjects. P1 and their current tactile artist had weekly meetings that lasted for two hours in total, during which they would discuss the design of the upcoming tactile graphics and their instruction strategies.

According to P1, S1 was proficient in reading tactile graphics independently and did not require much instructor support outside of pre-teaching sessions. S1 was accompanied by a para-educator during classroom lessons for any additional support. Additionally, S1 had previous experience using voice-over screen readers on an iPad for classroom activities.

Participant 2, also known as P2, worked as an itinerant orientation and mobility (O&M) instructor with 45 students in their school district. P2 created their own maps for one-time use, using braille embossed and wikki-sticks based tactile maps with braille labels.

For this study, P2 worked with S2, a middle school student who is visually impaired, once a week. During their sessions, they alternated between reading the tactile map in the classroom during study sessions, and navigating physical space outdoors using the map.

According to P2, S2 had been using Wikki-Sticks based tactile graphics since elementary school and is fluent in braille. S2 was able to independently read O&M maps, but struggled with using the tactile map for reference while navigating physical space. S2 frequently used their parents' phones with the voice over screen-reader and was fluent with voice over interaction gestures.

5.3.3 Data Collection

During the deployment, we employed a multifaceted data collection approach, incorporating various methods such as - weekly diary entries from TVIs, semi-structured weekly check-in interviews, weekly surveys, weekly design reviews with the TVIs to discuss designs for audio-tactile graphics, and one end-of-study interview. We chose these methods based on previous research that recommended similar participatory methods when assessing an assistive technology within the context of its use [122, 134].

During the 6-week period of T3 deployment, we collected data at the following points.:

- **Background Interviews**: At the start of the study, we conducted background interviews with the participants. The purpose was to understand their current collaboration practices with tactile artists (if any), their expectations for support from the research staff, and their educational goals for their students. It is important to mention that

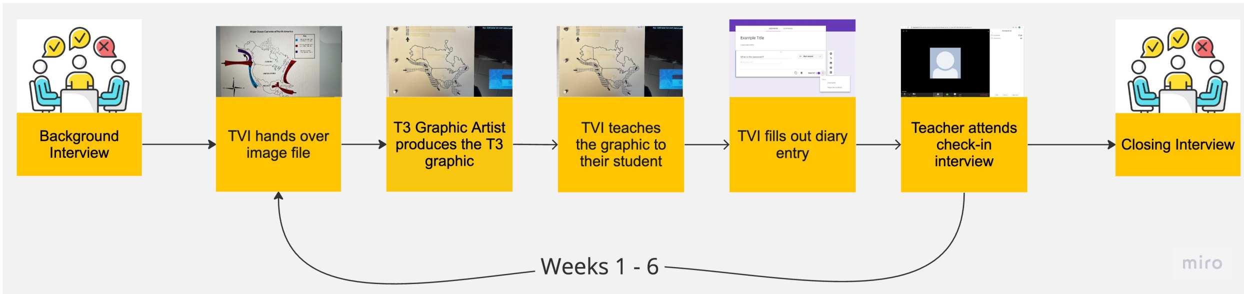


Figure 5.2: Data collection flowchart represents the sequential workflow and participant engagement throughout the study's duration. Initial Phase (Week 0): A background interview is conducted with participants to set the foundation for the study. Iterative Phase (Weeks 1-6): In a recurring weekly cycle, participants supply the T3 graphic artist with source images, which are then transcribed into tactile graphics. Following this, the TVI employs these graphics in student instruction, documents the experience via diary entries, and participates in a weekly check-in interview with the research team. This cycle is maintained for six weeks. Final Phase (Week 7): The study culminates with a closing interview between participants and researchers, covering the outcomes and experiences of the study period.

the participants in this study were TVIs, not the students. Therefore, we did not gather any information about the students and requested that any shared information be anonymized.

- **Weekly-Diary Entries**: Participants were asked to submit weekly diary entries whenever they used the T3 with their student.
- **Weekly Check-ins**: During the weekly check-in interviews, we reviewed the context in which participants used the audio-tactile graphics, discussed their feedback from the diary entries, and addressed any challenges that affected their students' experiences with the T3. In addition, we collected their survey responses regarding factors that influenced the adoption of T3, based on factors discussed by Phutane et al [161] and Holloway et al [88]. The survey questions asked participants to:
  - Comment on the difference in time spent teaching tactile graphics using T3 versus teaching without it.
  - Comment on the student's interest in using the T3 to access these tactile graphics.
  - Comment on the student's ability to independently read the tactile graphics provided using the T3, as compared to reading without it.
  - Comment on whether the student meets the expected pace of reading the tactile graphic.

  - Comment on whether they think that this graphic on the T3 could potentially be reused or repurposed for a different lesson or exercise.

- **Design Review**: The design review meetings provided TVIs with an opportunity to give feedback on the audio-tactile graphic designs prior to production.

- **End-of-study Interview**: At the conclusion of the study, we conducted interviews with the participants to assess the extent to which T3 assisted them in achieving their educational goals, as discussed in the background interviews. Additionally, we explored their overall experience with T3 during instruction, their students' experience with T3, and their collaboration with the T3 graphic artist. To facilitate the discussion, we utilized specific graphics generated during the study as artifacts, and delved into teaching strategies, challenges, and future opportunities associated with T3.

- **T3 Graphic Artist's Reflexive Memos**: The T3 graphic artist kept a journal of memos while supporting the participants. These notes served as reflections on their role as a T3 graphic artist and the challenges of being a researcher without formal training in tactile graphic design. T3 graphic artist instead followed conventional design guidelines that are popularly used when designing tactile graphic and met the requirements provided by the TVI participants. The memos also included insights from design review meetings, where TVI participants suggested changes to the initial designs. Additionally, the reflective memos documented specific details about the collaborations with participants, such as weekly schedules, coordination of graphic handovers, teaching strategies, and student preferences for tactile symbols and textures.

5.3.4 Analysis

The qualitative data analysis process was conducted systematically and iteratively. To maintain confidentiality, raw data, including audio recordings, field notes, and photos, underwent anonymization and transcription. We adopted an open coding approach to initially identify codes related to the T3's real-world usage. The initial coding was undertaken by the T3 Graphic Artist and subsequently refined and organized into preliminary categories by the research team. This was followed by a focused coding phase aimed at identifying recurring patterns and noteworthy findings at a higher level.

To enhance credibility and validity in the generation of high-level codes from the qualitative data, we also integrated quantitative usage metrics of initial codes and survey responses gathered during the field deployment. Additionally, end-of-study interview data was used to complement the analysis. Throughout this analytical process, we incorporated reflexivity by referring to design memos maintained by the T3 Graphic Artist. These memos documented personal assumptions and biases that emerged during their 6-week collaboration with the participants.

In summary, our qualitative data analysis adopted an inductive [80], iterative, and multidimensional [187] approach, yielding nuanced insights into the T3's support for our two participants over the 6-week period. The quotes in this paper have been modified for easier interpretation and to remove identifiable information about students' name, gender, age or other information protected under Family Education Rights and Privacy Act (FERPA).

5.4 Findings

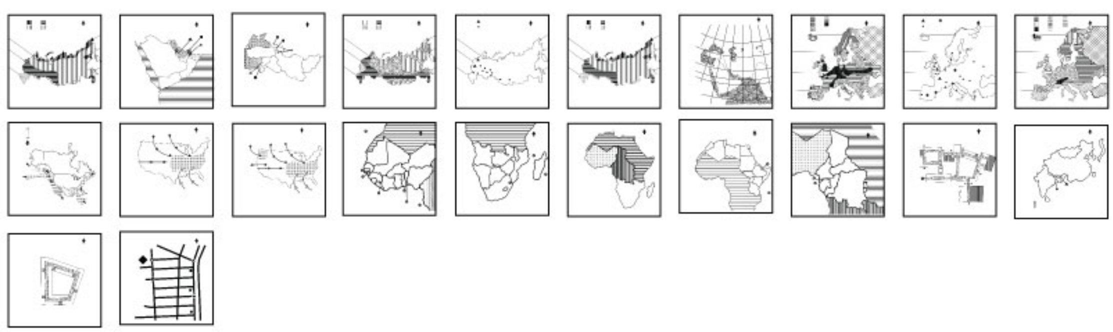


Figure 5.3: 22 tactile overlays produced for our participant during the deployment study. Of the total of 29 designs, 22 were finalized by our participants after going through the design review and improvements. High res copies of these graphics are available in Appendix C

This section presents the findings derived from the deployment phase. The first subsection delves into themes associated with factors influencing the adoption of the T3 within school settings. The second subsection evaluates the alignment of the T3 graphics design workflow with teachers' existing tactile graphics design workflow. Finally, the third subsection explores themes connected to the T3's effectiveness in achieving the educational outcomes outlined at the commencement of the deployment.

5.4.1 Factors Affecting The Adoption of T3 Graphics in Schools

In the previous section, we discussed previous studies which looked into the factors that influence which tactile materials TVIs choose for presenting graphics [88, 161]. We considered these factors in our study to understand how well the T3 tablet performed for our participants and its potential for long-term use in schools. In their responses to the survey questions as part of the weekly diary entries, our participants reported preferring to use T3 graphics over tactile graphics in most weeks. However, there were nuanced differences in their responses because P1 used the T3 for geography-related graphics in classroom and homework settings, and P2 used it to present orientation and mobility graphics in one-on-one study sessions and outdoor navigation activities. In this section, we present how our participants responded to the survey over the 6 weeks of the deployment.

5.4.1.1 Factor 1: Time spent teaching using T3 compared to traditional tactile graphics :

Table 5.1 lists participant responses to the question: *How much time did you spend teaching using the T3 graphics (T3Gs) as compared to braille labeled tactile graphics?*.

Table 5.1: Factor 1: How much time did you spend teaching using the T3 graphics (T3Gs) as compared to braille labeled tactile graphics?

P #	Week #1	Week 1	Week #3	Week #4	Week #5	Week #6
P1	Faster with T3Gs	Faster with T3Gs	Faster with T3Gsr	Exam Week	Faster with T3Gs	Faster with T3Gs
P2	Faster with T3Gs	Faster with T3Gs	Can't say	Practice Sheet	Can't say	Faster with T3Gs

Throughout the deployment, P1 consistently reported that their students exhibited faster reading capabilities with T3 Graphics as opposed to braille-labeled tactile graphics, resulting in substantial time savings. For instance, during a pre-teaching session of the T3 graphic of a map of the Middle East in week 3, P1 noted that they could effectively convey the material in half the time compared to utilizing conventional tactile graphics.:

> *"We probably spent 5 min introducing the graphic on the T3 before S1 was able to really dive in and figure out the countries…With regular tactile graphics, it would be probably like 15 to 20 min we would have to really guide them where everything is"*

Contrary to P1's findings, P2 discovered that T3 graphics were time-saving in teaching only in certain situations. P2's O&M exercises utilized a guided approach and physical navigation tasks. Although time was saved when introducing the graphic, working on the guided exercises and navigation tasks with the student often took the same amount of time as with traditional tactile graphics. P2 summarized this in their feedback after a navigation exercise in Week 3:

> *"Ultimately I don't think the T3 is necessarily saving me any time in the actual teaching. Where the T3 part comes in is that it allows S2 to be more independent when exploring a graphic and getting to what they think might be important, on their own".*

5.4.1.2 Factor 2: Student interest in the T3 :

Table 5.2 lists participant responses to the question: *Did your student show interest in using T3 graphics?.*

Table 5.2: Factor 2: Did your student show interest in using T3 graphics?

P #	**Week #1**	**Week 1**	**Week #3**	**Week #4**	**Week #5**	**Week #6**
P1	Yes	Yes	Yes	Exam Week	Yes	Yes
P2	Yes	Yes	Yes	Practice Sheet	Yes	Yes

During the deployment, both participants reported that the T3 graphics were engaging, and their students showed interest in reading them. P1 perceived the T3 as an interactive classroom tool, similar to the educational games used by S1's sighted peers on their computers.

> *"Our students who are sighted do DreamBox, and they do all of these digital games to help with math concepts and reading concepts[...] And then S1 misses out, because, whenever they're done with their work in class the kids are allowed to get on dream box. That's an activity they can do because it's school related [...] T3 is like that for S1 [...]I even thought that map from the example sheet was fun. S1 enjoyed it, and had a fun time trying to find all the answers and went through the full storyline"*

P2 also reported that their student expressed a keen interest in exploring the T3 graphics, indicating a positive attitude towards using the T3 for O&M maps.

> *"S2 loves it. S2 is always excited to read their maps so they starts querying everywhere on their own"*

5.4.1.3 Factor 3: Reusability of Audio-Tactile Graphics :

Table 5.3 lists participant responses to the question: *At any point did you try re-using or re-purposing this T3 graphic (T3G) for any other task than what it was initially designed for?*.

Table 5.3: Factor 3: At any point did you try re-using or re-purposing this T3 graphic (T3G) for any other task than what it was initially designed for?

P #	**Week #1**	**Week 1**	**Week #3**	**Week #4**	**Week #5**	**Week #6**
P1	T3G could be reused	T3G could be reused	T3G could be reused	Exam Week	T3G could be reused	T3G could be reused
P2	T3G could be reused	T3G couldn't be reused	T3G couldn't be reused	Practice Sheet	T3G could be reused	T3G could be reused

During the deployment, P1 repurposed T3 graphics that were initially created for classroom or independent study purposes. These graphics were used for tasks such as quizzes and homework. More information on how P1 repurposed the T3 graphics can be found in the next section.

In their background interview, P2 explained that they usually created Wikki Stix and embossed maps with limited detail for one-time use. As a result, the T3 maps produced during the deployment were highly specific to the lesson and not suitable for reuse in other activities:

> *"I usually pretty much do the same thing for everybody[...] 95% of the time I use wiki sticks and they're relatively effective. And usually you're just doing a small area at a time. Wiki sticks aren't durable and I can whip up something within 10 mins. They're pretty much one time use. There's no point in the mapping out 8 blocks worth of stuff."*

P2 did not typically work with a student for an extended period of time on a single lesson, which gave them no incentive to invest more time in building detailed and durable maps:

> *"No, I mean, if it's. if it's somebody who I mean it might get reused with the same student over a period of weeks or months potentially but rarely does it come up where whatever issue they're having"*

On occasions when P2 considered reusing a T3 Graphic, it was to add braille markers so S2 could use the tactile overlay without the T3 when navigating spaces:

"I plan on having S2 take it with them when we go over to the school. And what I'm curious about is - without the T3, how much of it are they going to actually recall and if I need to add some braille to it"

5.4.1.4 Factor 4: Fostering Independence in Reading Graphics:

Table 5.4 lists participant responses to the question: *Did the T3 grphic support your student in exploring the graphic independently?*.

Table 5.4: Factor 4: Did the T3 grphic support your student in exploring the graphic independently?

P #	Week #1	Week 1	Week #3	Week #4	Week #5	Week #6
P1	Yes	Yes	Yes	Exam Week	Yes	Yes
P2	Yes	Yes	Yes	Practice Sheet	Yes	Yes

During the study, both participants observed that their students demonstrated increased independence when reading tactile graphics on the T3, as compared to traditional tactile graphics.

P1 noted that this independence was evident in reduced reliance on para-educators and TVIs for assistance, improved ability to develop reading strategies independently, and faster access to audio labels. Participant 2 observed that greater independence allowed their student to interpret graphics with minimal assistance. The following section on participants' education outcomes explores the specific design features of the T3 graphics that facilitated independence among students in their respective use cases.

5.4.1.5 Factor 5: Meeting the Expected Pace of Reading :

Table 5.5 lists participant responses to the question: *Did your student meet the expected pace when reading the T3 graphic?*.

During the deployment study, both participants observed that their students were able to maintain the expected reading pace. The participants frequently reported that students read T3 graphics faster than braille-labeled tactile graphics. They attributed this to the immediate feedback provided by accessing the audio labels. The increased speed and independence in reading tactile graphics allowed the students to actively engage with their sighted peers during classroom activities using the T3. Participant 1 recognized the T3's potential to support similar collaborative activities in mixed-ability classrooms over an extended period. In

Table 5.5: Factor 5: Did your student meet the expected pace when reading the T3 graphic?

P #	Week #1	Week 1	Week #3	Week #4	Week #5	Week #6
P1	Yes	Yes	Yes	Exam Week	Yes	Yes
P2	Yes	Yes	Yes	Practice Sheet	Yes	Yes

the next section, we will explore the T3's features that facilitate faster learning and support both existing and innovative teaching strategies for our participants.

5.4.2 T3 Graphics Production Workflow During Deployment

During the study, both the T3 and T3 workflow were tested in a real-world scenario. We followed the complete steps of a traditional tactile graphic workflow. This included designing the graphic based on our participants' timelines, making real-time modifications, and using the graphics for teaching purposes. These efforts facilitated a deeper understanding of how stakeholders, including the T3 Graphic Artist, educators, and students, engage with the T3 at various stages within an educational environment. Our findings highlight both the commonalities and distinctions between the workflows involved in designing, editing, and instructing with T3 graphics in contrast to those associated with traditional tactile graphics

5.4.2.1 Compatibility with Tactile Graphics Production Workflow :

To ensure the successful integration of the T3 into school environments, it is crucial to ensure compatibility with educators' existing tactile graphic workflows. Throughout the T3 deployment, participants provided valuable insights on the similarities and differences between their conventional tactile graphic workflow and the T3 workflow. This section summarizes participants' comments on their respective workflows.

P1 collaborated with a tactile graphic artist, classroom teacher, and para-educator (TA) to plan the inclusion of tactile graphics in S1's curriculum. This collaborative effort required 1-2 hours of weekly time-load:

> *"I have about 1-2 times a week that we meet for 1-2 hrs per week. I work on, collaborating with the TA, (classroom) teachers and the tactile graphic artist about how to make the graphic, what's important, what can be eliminated".*

Throughout the study, the T3 Graphic Artist successfully adhered to the established timelines and quality standards for the T3 graphics used by P1 and their student, all while ensuring that it did not impose an additional burden on P1's customary workload. However, it is important to note that in a real-world, non-study context, the responsibilities carried out by the T3 Graphic Artist would typically fall within the purview of a tactile artist. Tactile graphic artists typically operate in an itinerant capacity, providing support to multiple TVIs and students across various schools within a county. Determining the precise impact of integrating the T3 into a tactile artist's workload posed a challenge, particularly considering that the tactile artist with whom P1 collaborated also assisted several other TVIs and students throughout the county:

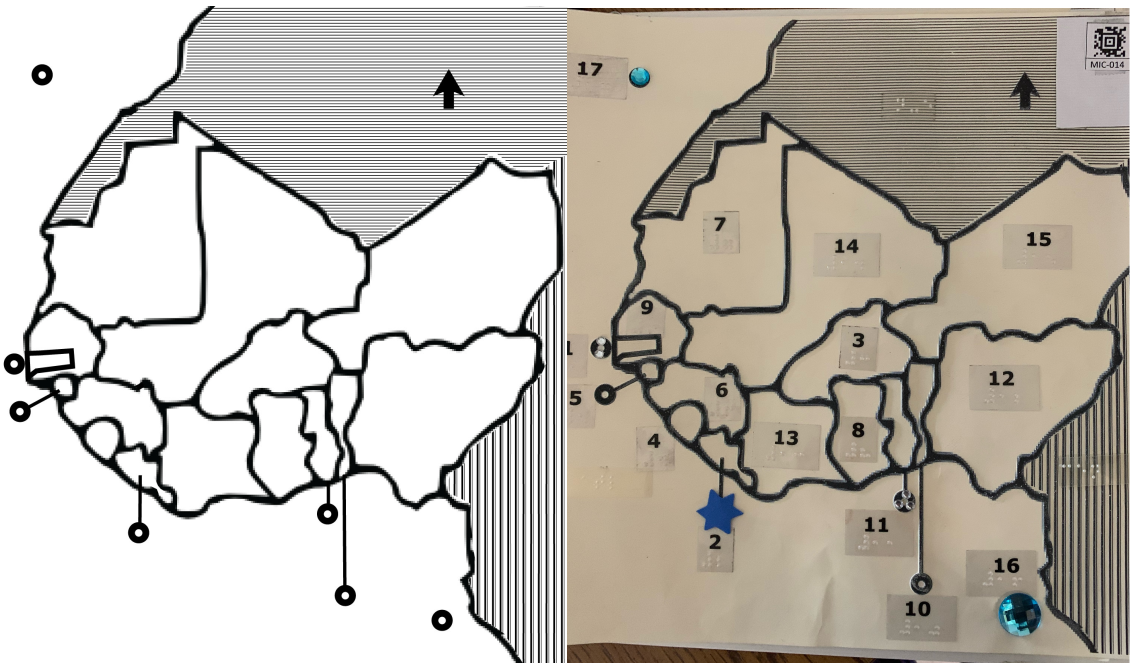
> *"whatever time I spent with you discussing the graphics is about the time I would spend with my tactile graphic artist to design it... I feel like you got it done, maybe slightly faster. But I don't know, what you do in addition to just making graphics for my students. Because the tactile artist is making graphics for all the kids in the county, and the braille text, and then collaborating with 7 other teachers"*

While the adoption of the T3 did not introduce substantial changes to the workflow for P1 and their TA in terms of teaching, it is essential to note that our present research did not investigate the potential impact of our ad-hoc T3 graphic production process on the workload of tactile artists. We intend to address this open question in future research as we refine our ad-hoc production process based on insights gained from this study.

Modification of Tactile Overlay:

Throughout our deployment, P1 described the process of modifying T3 graphics as akin to the adjustments typically made when modifying braille-labeled tactile graphics. In Week 2, for instance, S1 encountered difficulty in memorizing a graphic due to the uniformity of tactile symbols located at the end of the lead line. P1 effectively addressed this concern during the pre-teaching session by implementing real-time corrections to the graphic, guided by the student's feedback. This involved the application of tactile stickers, a common practice in modifying braille-labeled tactile graphics, to alter the shapes of select symbols on the T3 overlay.

> *"S1 was memorizing shapes because S1 is a blind student who learns visually, which is really funny. As S1 was learning the country, they would create a shape in their mind like - that country looked like a guitar to S1. And then the circles [tactile symbols] going to the smaller countries all were circles for S1 (ref fig 5.4a) . So I put the dots right on the page (ref fig 5.4b). As I was working with S1, I just went and grabbed the sticker dots. We have just available in a box for us because we like to keep them handy if we need to make changes, we label stuff*



(a) Original Tactile Overlay

(b) Modified overlay with tactile stickers

Figure 5.4: A graphic depicting the countries in West Africa was part of P1's curriculum for S1. Figure (a) shows the version created by the T3 graphic artist, which features hollow circular tactile markers to represent smaller countries and islands. Figure (b) is a photo of the modified graphic shared by P1 with the researchers. In this modified version, some of the tactile markers were replaced with tactile stickers, similar to the way P1 would modify traditional braille labeled tactile graphics.

for S1 on the fly. So I was able to just do it right there on the T3. I didn't even take the sheet off the T3 and just put them right on. And then S1 was like - 'oh, okay, I understand the difference now'. And so they were able to access it right away."

P2 did not discuss any situation where they had to modify the tactile overlay of any T3 graphic.

Modifying Audio-labels:

Both participants had access to the audio label databases associated with the T3 graphics. They would often correct or elaborate upon audio labels in their T3 graphics by making modifications to the database in real-time. Both participants acknowledged that making corrections on the T3 would not increase their workload compared to making corrections on braille-labeled tactile graphics, if the T3 were integrated into their daily use:

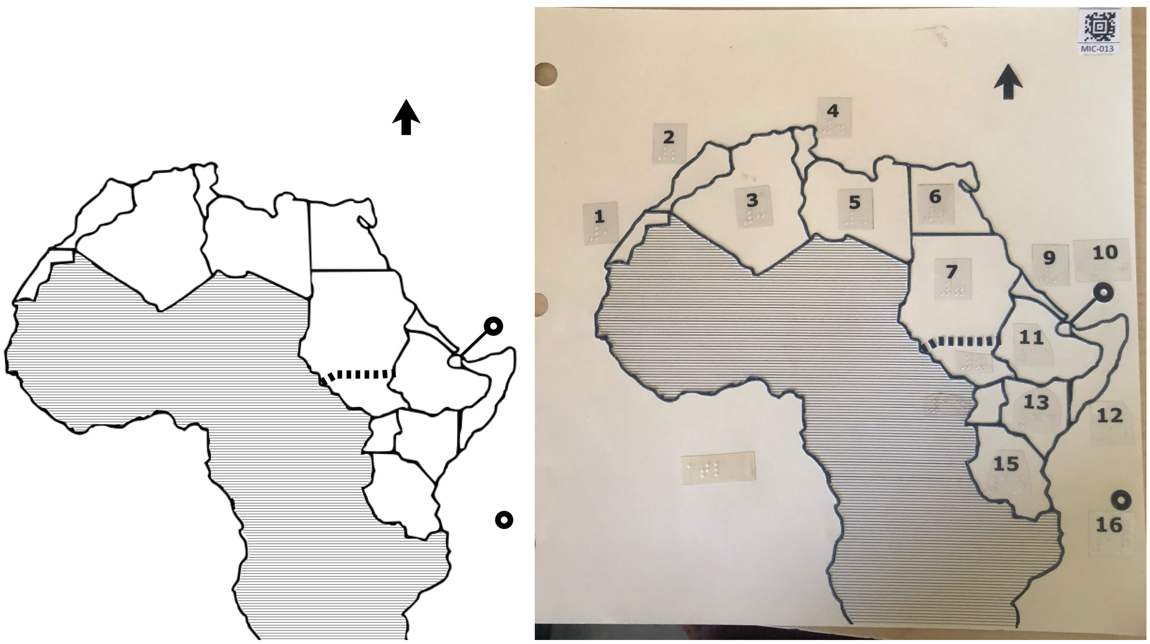
> **P1**: *"if the graphic was already made, I feel like it might be just similar. I guess it would be about the same if the graphic would be already made. For S1 to access it would be faster with the T3. But I think for me I feel like it would be the same. Because then you're just putting it within that database."*

> **P2**: *"I want to say like, I think it would be about the same... for this lesson I just put a note in there that said 'hello' or something like their name. And it would talk back to S2, and then I could do it right there while they were there. They'd just hear me type in, and all right. Try it again and there's a different noise"*

Re-purposing a Graphic:

During the background interview, P1 explained that they often repurposed braille-labeled tactile graphics originally designed for classroom use for other tasks such as homework, quizzes, and independent study exercises. This process involved covering up the braille labels. However, in doing so, they sometimes had to modify other tactile features of the graphics for the student by covering up tactile lines that were not part of the labels or failing to sufficiently cover up the braille labels:

> *"on a actual graphic, we had to cover up all the braille, which then changed the map to look different than what S1 got from studying it [...] by trying to cover up sometimes lines would get covered just because you're trying to manipulate it. or like when you're trying to cover labels with a piece of paper, S1 might be able to feel the braille through it like so it was hard to be able to like actually know like if we were covering it properly"*



(a) Original tactile overlay (b) Braille and print stickers added to the overlay

Figure 5.5: A graphic depicting the countries in East Africa was included in P1's curriculum for S1. Figure (a) displays the version created by the T3 graphic artist, which does not include braille labels for the countries. P1 wanted S1 to study this graphic using only audio labels. Figure (b) is a photograph of the modified graphic shared by P1, which includes braille and print labels for the countries. This modified version was used as a quiz sheet, where the student wrote the names of the countries corresponding to the numbers, using the overlay without the T3 tablet.

During the deployment, P1 made modifications to the T3 graphic by adding numbers to the tactile items used in the quiz. This approach required less tactile manipulation since there were no braille labels to cover up, but still achieved the same result. In addition, when P1 wanted to remove labels entirely before the quiz, they would use the tactile overlay without the T3 tablet for quiz activities.

> *"so I think that the T3 was better because it (tactile overlay) didn't change much. So nothing changed on it. I mean, we did add braille labels like 1, 2, 3, 4 so S1 could match the country. And we had a list on S1's braille note of the countries and S1 would just say the braille label number one is, South Africa. Braille label number two is Kenya. Right? but the overlay really didn't change much"*

During the deployment, P2 did not feel the need to modify the tactile overlay created for the study session when using it for navigation exercise sessions.

In summary, for our participants, the workload, tools used, and the time required for modifying a T3 graphic were similar, if not easier in few instances, than those for a braille-labeled tactile graphic.

5.4.2.2 Compatibility with current and novel teaching pedagogies:

Throughout our study, both participants employed the T3 for a variety of tasks, spanning classroom activities, homework assignments, and study sessions. They described utilizing teaching strategies similar to those used with braille-labeled tactile graphics. Furthermore, participants also explored innovative pedagogical approaches that were uniquely enabled by the T3 and not achievable with braille-labeled tactile graphics. This section offers an overview of the T3's compatibility with current teaching pedagogies and discusses few novel pedagogical methods specific to the T3.

In the previous section, we discussed how P1 transformed T3 graphics from study sheets into quiz sheets. This modification enabled a variety of teaching activities, such as take-home quizzes, independent study sessions, and homework assignments, similar to those supported by braille graphics:

> *"So the TA just put the numbers on the graphic. and then they are going to give S1 a braille list with those numbers so they can study when they're at home. And then when S1 takes the test that they'll just write whatever country is next to that number like the number of it […]We sent the T3 home for them to study.. And then S1 came back in class and then they took the test... So they did take the test in the classroom... But S1 didn't have the T3 for that. They just had the graphic because obviously we don't want to announce what that country is"*

Likewise, P2 detailed their implementation of a *"follow-along"* exercise - a common teaching technique in orientation and mobility training. They utilized a T3 graphic portraying the layout of a middle school for these exercises. The objective of these activities was to assist their student in cultivating route knowledge between two specific points on the map:

> *"I said to S2, follow your route from the gym to the cafeteria and then over to 109 room, right? Because those are on there, and it just shows them that you have to go through a couple of different hallways that are different names. Essentially, S2 could feel it there. It's pretty much a straight route. You don't really have to make any turns... And then, I programmed it in the column that - from here saying things like go to from the math hallway to the library hallway and then to 600 hallway and then having them try to hit their checkpoints along the way"*

In the initial part of this quote, P2 outlines a teaching strategy to build map knowledge. S2 was tasked with locating and connecting landmarks such as the gym, cafeteria, and room 109, effectively tracing a route that links these key points. In the latter portion of the quote, P2 introduces the incorporation of navigation instructions within the second layer of the tactile graphics. Here, P2 encouraged their student to discover these guidance notes while navigating the designated route. P2 noted that they typically did not include extensive notes in their Wikki Stix maps; however, the utilization of layered audio labels offered the opportunity to integrate additional details aimed at facilitating the development of route knowledge for S2. P2's intention was to introduce navigation cues related to the physical environment, encompassing factors like the floor's texture and lighting conditions (especially for students sensitive to light), into the navigation instructions.

> *"there's a slight texture change between those 2 hallways. They redid the floor at one point and the other at a different time. So if you've got really good cane skills, and you're really in tune with what the cane's telling you, you can feel a little bit of a texture change[...]we could add all that to the announcement"*

During the study sessions, P2 noticed that S2 was able to answer questions more quickly when using T3 maps. However, this did not result in any improvements to their performance in physical space during navigation exercises. To determine if providing additional details in audio-labels could enhance the development of route knowledge and navigation skills during O&M exercises, further studies that control for the student's navigation skills would be required.

5.4.2.3 Pre-requisite skills and training for students:

We intentionally recruited participants for our deployment who possessed a minimum of four years of experience in instructing students proficient in reading tactile graphics and well-versed in swiping gestures for tablet-based screen readers. However, our study highlighted the necessity for additional training strategies aimed at cultivating exploration procedures specifically tailored for T3-based audio-tactile graphics.

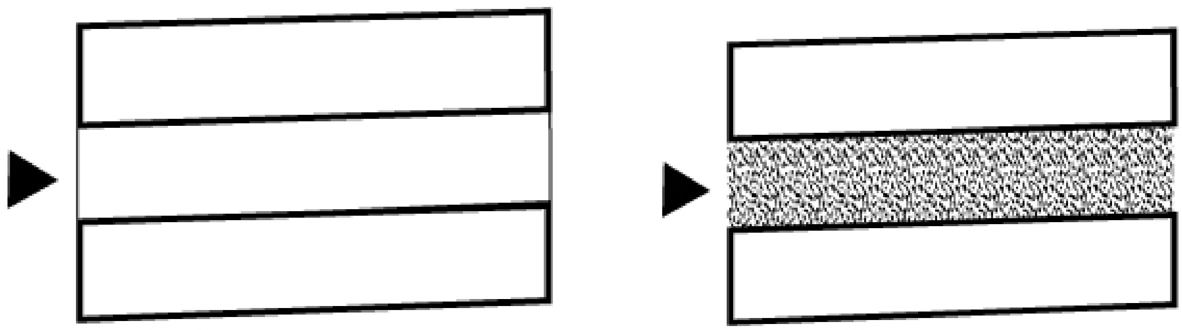
One participant acknowledged that the T3 is an advanced access technology that builds upon the braille and tactile graphic skills that students have already acquired. As such, it is not intended to be introduced at a foundational level, nor does it justify replacing braille-labeled tactile graphics with audio-tactile graphics during earlier stages of learning.

> *"because our goal here is to show them all the different versions of their way to access a graphic. So we will still teach them how to read a tactile graphic out of a textbook, so they know how to do that and look at a key. And that way they have that ability to be able to adapt [...] Tactile graphics are like that building block. We would still definitely teach that skill only because we know they're not going to have a T3 everywhere[...] That's something that it would be like probably in upper middle school or lower middle school to introduce. I feel like maybe a little earlier also since a lot of times the technology does come around third grade, and so they would have that skill in that development there."*

P1 and P2 also recognized the need to teach students different exploration techniques when interpreting T3 graphics, as compared to their usual methods for interpreting braille-labeled tactile graphics. This adaptation was necessary due to the inherent differences between audio labels and braille labels in relation to tactile elements.

For example, during a discussion about a floor map of a middle school, P2 shared a scenario where a student used a different exploration technique with the T3 graphic compared to their usual approach with braille labels. Traditionally, a braille label placed in the middle of a corridor, indicated by empty space between two solid lines, served as a landmark for the student to identify the corridor. However, with a T3 graphic map, the student needed to first identify the corridor through the solid lines and empty space, and then locate the associated audio label. S2 faced difficulties in identifying the corridor without a braille label, as it was now represented solely by empty space between two solid lines, without any tactile landmark.

> *"S2 was more like, Well, okay. So my landmark is just now like the middle of the hallway, where I'm pressing as opposed to some physical feature, you know,*



(a) Original corridor and rooms design (b) New design for rooms and corridor

Figure 5.6: A graphic depicting the two variations of designs used in indoor floorplans for P2 and S2. Figure (a) displays the version created by the T3 graphic artist, which does not include a texture marking the corridor distinctly, however rooms contain a solid raised border defining them. Figure (b) is a revised corridor design to be marked with a distinct rough texture that separates it from the room, in addition to the raised borders, based on S2's feedback.

> *which is kind of the opposite of how we would, teach you where you're physically you know, using your cane to look for something. That's my landmark. I know I want to pass that in order to get there, or even just to build confidence that Yep, I'm on the right path".*

In response to this feedback, we introduced modifications to our tactile design. These adaptations involved the incorporation of distinctive tactile textures to represent corridors, effectively designating them as identifiable landmarks on the map that one could query for audio-labels. Furthermore, P2 undertook the task of training the student to systematically search for audio labels within empty spaces before presuming they had ventured beyond the boundaries of the building. This approach to exploring the T3's tactile overlay deviated from S2's prior experience with reading braille-labeled tactile maps.

Notably, it became evident during the study that the students' exploration procedures with T3 graphics were influenced by pre-existing challenges they encountered when exploring tactile graphics. For instance, S2 utilized the tip of their index finger for reading both patterns in tactile graphics and braille text. P2 noted that while this approach was not conventional for reading tactile materials, it was a skill that S2 had developed before they began working with P2.

> *"when S2 reads Braille they just using one finger, and S2 told me that my other*

fingers can't read braille[...]I wasn't there when they learned how to read braille so I don't know how it happened."

In the past, P2 had not encountered any issues with S2's approach of reading tactile graphics using the tip of their finger. S2 effectively read the lines and braille labels on tactile graphics crafted by P2, which were produced using Wikki Stix and a braille embosser. However, a challenge arose when T3 graphics featured elements represented as spaces wider than the tip of S2's index finger:

> *"S2 can trace the hallway with their finger and know exactly where they are in that hallway, but not anything that's not directly in the center of that finger. So I don't know. Do we make the corridors a little bit smaller, you know, so that you almost have to feel something while you're going along it. Or is that just something they needs to work on to, you know. Put a second finger there to feel for other things as you're going along. I don't know I haven't quite figured that one out yet".*

P2 acknowledged that their student might require an extended period beyond the study's duration to fully adapt to a new approach for interpreting the graphics. Consequently, we made the deliberate choice to design future T3 graphics in a manner that harmonized with the student's existing exploration techniques:

> *"Let's say this is the ideal solution that S2 just has to train, another finger and get their brain to be paying attention to what's going on in that second finger in addition to their index finger that S2 typically reads braille with. And if we did this for the next, you know 3 weeks worth of lessons. Would you catch on to it? or would this take longer? I did not work with S2 when they were learning to read Braille, so I don't know did it take S2 6 months to the take or 2 years. So is the work around in the meantime to make the hallway narrower? Or is it something that they are going to be able to teach themselves how to do with enough practice?"*

P1 emphasized the significance of guiding their students in adopting a systematic exploration process for T3 graphics, commencing from the top and progressing from left to right. This methodology had previously been instilled in the students for reading braille-labeled tactile graphics and proved to be beneficial when navigating T3 graphics, particularly those with more intricate details than braille-labeled graphics. P1 noted that S1 exhibited a relatively more *'random'* exploration style, often pressing various points on the graphic to access labels. This divergence in exploration methods could be attributed to the ease of swiftly accessing audio labels and the heightened level of detail present in T3 graphics compared to braille-labeled tactile graphics:

> *"You see, when S1 is reading tactile graphics as well that they would sort of miss out on. S1's a little impatient, and so I think they just want to get it all in, but then, like misses it, so they're not very systematic in general[...] On T3 they started like pushing all the spots to see what everything was and I think the first graph S1 did get everything. So when it got more complex I did have to kind of guide them in a way because it was like they were missing some of the graphic , like some of the pieces because of that. But I think just because there was so much more on there. So that's something I'll have to work on with S1 with is like because they just kind of randomly start pushing things. I do have to work with S1 on going top to bottom, left to right. Just make sure you get all the pieces of the graph [...] maybe that is something we can include for them in the announcement at the start to look for all these things, these many markers on the sheet"*

In summary, the utilization of T3 graphics within the classroom context demonstrates promise in terms of compatibility with existing tactile graphic design workflows. Moreover, T3 offers the capability for real-time modifications to the tactile overlay and audio labels, similar to braille-labeled tactile graphics. Additionally, T3 accommodates conventional teaching pedagogies and possesses the potential to facilitate innovative teaching methodologies, such as the incorporation of detailed navigation notes during 'follow-along' O&M exercises. Nevertheless, it is essential to acknowledge that students may necessitate additional training to cultivate exploration techniques specifically tailored for T3-based audio-tactile graphics.

5.4.3 Participants' Education Outcomes Surrounding Use of T3 Graphics

At the start of the study, participants discussed various educational outcomes they hoped to achieve by using the T3 to teach their students. In this section, we will delve into the themes that influenced the participants' experiences with the T3 in attaining these outcomes. We will also explore instances where the T3 did not support these desired outcomes. Our specific focus will be on the following educational goals:

- Improving speed and autonomy when reading tactile graphics using the T3

- Providing tactile graphics with richer details
- Creating interactive tactile graphics
- Supporting complex tasks using audio-tactile graphics
- Closing the disparity in the classroom experiences of blind and sighted students.

5.4.3.1 Outcome 1: Improving Speed and Autonomy When Reading Tactile Graphics Using the T3.

P1's goal for the deployment was to improve the independence of their student in reading tactile graphics, requiring less assistance from the para-educator and TVI:

> *"Getting S1 to access some of the graphics in a way that they can be more independent".*

For students with visual impairments, exploring tactile graphics may take longer than it takes for sighted students to explore print graphics. This is because of inherent differences in visual and tactile perception channels [137, 120]. As a result, it can be challenging for them to keep up with the pace of classroom instruction, which can impact their overall classroom experience.

> *"So sometimes they go through the graphics so fast that S1 doesn't have enough time to look at it. Because as a sighted person, you can get a snapshot quickly of what is being described like. So the teachers like, Oh, this is France, and here's Paris, right? But S1 is literally going in a grid to feel what it looks like. And then where's Paris. And by then they've already moved on. So it's basically double time for them to like view the same thing that their sighted peers are viewing. S1 has to feel it and it takes a little bit.... And so sometimes it is just explained to S1 verbally - this is, what you're seeing, this is what we're going over"*

During the deployment, both participants reported an improvement in the time their students spent familiarizing themselves with tactile graphics. They attributed this improvement to the *"immediate feedback"* provided by co-located audio labels. As a result, the level of assistance required from TVIs or para-educators was significantly lower for T3 graphics, allowing students to explore tactile graphics more independently:

> *"S1 does it much more independently. There's a lot of pre teaching for a braille graphic, because we have to verbally sometimes tell them what it is, or what they're looking at right? And on the T3, all S1 has to do is ,while they're looking*

at it, just push it and the T3 says it. So the TA or I am basically eliminated out of that interaction. Like for instance if the key is not making sense to S1, instead of going back and forth or asking me about it immediately, they are touching it and It gives them that feedback independently without having an extra step for asking us what it is?"

When it comes to S1, querying for information that is usually found in a key, located in the same place as the tactile element, significantly reduced the time and effort required for reorienting. In contrast, it was common for P1 to assist S1 in reorienting when they switched between a braille-labeled tactile graphic and its corresponding key. As a result, P1 reported that pre-teaching sessions were faster with a T3 than with braille-labeled tactile graphics:

"I would say we spent under 10 min with the T3 [...] It would probably close to more like a half hour if it was with a tactile graphic with the key that S1 had to go back and forth...(with a braille labeled tactile graphic) it would have been more hand over hand kind of teaching and helping them go find their spot again. Because a lot of times when you pull your hands off and you have to reacclimatize yourself to the graphic and figure out where you are and what you're doing"

Similar to S1, P2 described improvements to S2's ability to independently explore O&M maps. This allows S2 to *"ask their own questions"* to T3, rather than relying on P2 for guidance:

"Once the graphic is up, they're independent, and able to follow the directions...I mean, ultimately I don't know that S2 was interpreting it better but they absolutely was more comfortable using the T3 because again, it's instant feedback you know, you're asking yourself your own questions and you're doing your own thing while you're right there. This is what I want to know about their learning, not what they're asking me. Its like instead of formulating a question to ask me, S2 can just ask the T3, that's what I want to know about it"

When asked about any noticeable differences in the amount of time spent teaching a graphic with the T3 compared to without it, P2 noted that using the T3 resulted in significant time savings during the initial exploration of a map:

"We spent just less than 10 min. I didn't time it, but it was definitely less than 10 min for them to go through it. I know they're anticipating some questions that I'm going to ask, because I have some pretty consistent ones that I ask. S2 wasn't able to do all those things, and we had to go through it step by step, like - What's

the northernmost, east-most, west-most, street on this map? Have them find it and answer... (with a Wikki Stix map) It that would have taken us a whole lesson of 45 min. So that's a pretty dramatic time saving there in the actual exploration of the graphic before we could even start, seeing if S2 really understands where things in the physical world"

However, P2 did not observe a significant difference in their students' ability to answer questions more accurately or navigate physical spaces better using the knowledge gained from T3-based maps:

"S2 doesn't necessarily do a better job of, you know, answering questions or anything, But I think it's more independent for them that they're doing more of the interpretation and less of me doing the interpretation"

It is important to note that the level of independence displayed by students in reading tactile graphics did not always result in time saved during teaching. While P1 used the T3 tablet in both classrooms and study rooms, P2's teaching included physical navigation exercises that did not allow the use of the T3 tablet, but only the tactile overlay. As a result, S2 used audio-tactile graphics solely for initial exploration, but not for the physical navigation exercises, due to the nature of O&M exercises.

5.4.3.2 Outcome 2: Improvements to the level of detail in a tactile graphic:

Braille-labeled tactile graphics often fail to convey all the details present in the original visual image. Our participants frequently encountered this issue when using braille-labeled tactile graphics with their students. One participant mentioned that complex graphics were sometimes explained verbally to their students, either because of last-minute planning by the classroom teacher or because the intricacies of the graphics could not be accurately represented in a tactile format. The participant's goal with the T3 was to ensure that visually impaired students receive the same level of detail in graphics as their sighted peers:

"sometimes S1 doesn't get the graphic because the teacher decided we're going to do this today and its last minute. And so then it's just verbally given to S1. So sometimes they are not quite accessing the graphic. So it would be great if S1 could always access graphic just as all their sighted peers... a graphic for a sighted person gives you a lot of information, but for a blind person, it's not as detailed. And so that would be nice"

We noted that the following aspects of the T3 supported our participants achieve this outcome during our deployment study:

Higher Information Density:

Participants noted that the T3 afforded them greater complexity in graphics of the same size as braille-labeled tactile graphics. This was possible because the audio modality could convey information typically presented in braille labels, freeing up the tactile medium to convey more non-textual details. As a result, the T3 graphics effectively communicated complex concepts.

For instance, S1 required a map to compare population density and climate in Europe, illustrating how climate affects population density. After discussing with P1, we chose to divide the source image into three graphics: one explaining climate patterns in which the audio-labels announced temperature ranges associated with each zone, a second one explaining population density patterns in which audio-labels contained details about the population density range, and a third one displaying cities in which the audio-labels contained specific population for cities.

When asked if our T3 graphic successfully provided the details as well as a braille-labeled tactile graphic, P1 replied that S1 was able to read individual graphics faster and therefore gained a better understanding of the correlation between population density and climate across the three graphics:

> *"I think so. Because it had a lot of detail and S1 was able to then go through and really like to identify where the heavier, more densely populated areas were versus not and then look at the climate maps. In like a regular graphic, I feel like S1 wouldn't have gotten as much feedback about knowing exactly where the dense population was and the density numbers. And also they were able to move around easier where like on a regular graphic, it's like S1 would have to really like keep referencing that key. And so I think it did give S1 more detail with that immediate feedback without having to like raise your hand up off the map and then have to go back and forth. And then a lot of times it would have taken us over multiple (braille-labeled) graphics where like the T3 was able to give S1 all that information within one graphic each"*

Accurate Connection Between Labels and Tactile Elements:

P2 recognized that audio labels provide a more accurate connection to the associated tactile element compared to braille labels. Braille labels are often placed near an element and can be interpreted differently due to their ambiguous positioning.

“the labeling is always tough, because unless it is you know, almost directly attached to the line you’re looking for, it gets pretty It gets vague, and you know, indistinct. Right? Okay, I’ve got these 2 lines here that are representing a road. But then I only have one name for the road. Right is it? Am I? Is the road for the top? Is it for the bottom you know which one am I really looking at here, trying to feel and then being able to”

Although it didn’t directly enhance the graphic’s level of detail, it effectively diminished the requirement for elements like lead lines, which are typically employed in braille-labeled tactile graphics to mitigate potential ambiguity associated with the braille labels.

Adding Details to Cascading Layers:

Cascading audio-labels as layers allowed us to add additional details to a T3 graphic than braille labeled graphic. These layers could be accessed by pressing again on the associated element to query deeper, which further increased the amount of detail that could be encoded in the graphic for our participants. For instance, on street maps, P2 requested that details about intersections, such as stop signs and signals, be embedded as cascading audio label layers:

“the next thing I wanted to look at was that at all the intersections the first layer would be the name in the intersection, next one is the shape of the intersection and then the next one down is what is the traffic control at that intersection? I haven’t quite completely gone through all the intersections yet to tell you what the traffic control is, but I can put that in later. You know - do I have stop signs on one street? Do I have stop signs on both streets? do I have traffic light? Once you have that intersection labeled, If there’s something there that is a unique landmark like a couple of like the Dairy Queen and Jets Pizza, and the Coney Island which most of these really have”

5.4.3.3 Outcome 3: Making tactile graphics interactive

P1 reported that S1 often lacked access to interactive educational materials, such as the Dream Box - a collection of computer-based learning games [51]. These materials were used by their sighted peers in the classroom as supplementary educational resources.

“So, like our students who are sighted they get the dream box. So they do all of these digital games to help them with math concepts and reading concepts. The T3 could be something like that for S1... because all the sighted kids get that. And then they miss out on that, because, like whenever they’re done with their work

in class the kids are allowed to get on dream box and like that's an activity there they can do because it's school related. But it's also like fun games that they can kind of like in a way turn their brain off, even though they're still learning so I think the T3 will be good for that and it would be building S1's map skills like the dream box games"

P1 discussed the analogies in their student's experience when using T3 graphics compared to interactive classroom games employed by sighted students. The T3 introduced elements of independence and interactivity, including pre-programmed Q&A sheets and exploration prompts. These features notably bridged the gap, rendering the classroom experience for P1's student more akin to that of their sighted peers, in contrast to tactile-only interfaces like braille readers:

"So the the interactivity of this is pretty cool because it's similar to those games that sighted kids are are using... it's independent... So for the Braille Keyboard games, we do rows of contractions, and then it comes out into a picture of a like a pumpkin. A lot of times I verbally tell them- you have to type a G-H contraction. And they have to remember what the G-H contraction is. Because, if they get it wrong, their braille picture is not going to turn out right. But that's not them being independent. And so this [T3] would allow S1 to do that, because S1 did that one T3 graphic map game independently like I introduced it them when they were just learning what the T3 was at the time, but then they did it independently, and followed along with the game, and it talked to S1 about what to do next and they did it like all our sighted kids would do on the computer through their activity in their games. So what I liked about it was at the same playing level field as other kids."

5.4.3.4 Outcome 4: Closing the Gap in Classroom Education Quality between Sighted and Blind Children

P1's primary objective was to bridge the gap between the classroom experiences of their blind student and their sighted peers through the utilization of the T3. Upon comparing the classroom experiences of S1 when they used tactile graphics with the experiences of sighted students in their classroom, P1 discerned disparities in level of detail, interactivity, and overall inclusion in collaborative classroom activities.

During our discussion with P1, we learned how the T3 significantly enhanced reading speed, interactivity in the process of interpreting tactile graphics, and the level of detail presented in the graphics that S1 used. These enhancements, coupled with the audio-visual nature of T3-based tactile graphics which made them easy to read for sighted colleagues, were recognized to exemplify a form of 'universal design' in learning. This approach seeks to facilitate the inclusion of blind students in classroom activities alongside their sighted peers. P1's observation also indicates that, unlike braille-labeled tactile graphics, T3 graphics closely resembled the graphics typically used by sighted students. This similarity in visual representation is essential for fostering collaborative work, and the T3 presents an opportunity to facilitate such collaboration.

> *"I think (the T3) would work really well in classroom setting. Especially because a lot of times they would team up in partners and discuss the graphic with a partner, and they would be able to do that with a partner...like some of the science ones they did and got together with partners and talked about them. So it would be, I think the T3 would be successful in class... Because they were able to independently do it without an adult there. And so because it was partially visual that the other student could still access that. It's a universal design, its very cool"*

It should be noted that P1's student only used the T3 with a sighted peer for one lesson during the 6-week deployment. Therefore, P1's comment about the opportunities for using T3-based graphics in collaborative learning settings among sighted and blind students is based on this one instance. In that instance, S1 worked with a sighted colleague on the T3 while the classroom teacher taught the concept of latitude and longitude lines over a map.

> *"S1 had done latitude longitude lines before this. I know they were partners, so they did break out into groups to do this lesson together with other kids... I don't know exactly how it went because I wasn't in class. The TA was just relaying all this information to me. I don't know exactly how the teacher was teaching it."*

In this scenario, P1 observed that T3 graphics, which were audio-tactile for P1's student and audio-visual for the sighted partner, made classroom activities more inclusive as compared to other braille-labeled tactile graphics. This was a brief activity that was later assigned as an exercise (discussed further in the next section). However, it raises important questions about the opportunities for using audio-tactile graphics in mixed-ability classrooms.

5.4.3.5 Outcome 5: Designing graphics that support complex tasks:

T3 facilitates a diverse range of interactive tasks, as acknowledged by both participants in their teaching experiences. While tactile graphics also typically support such complex tasks, T3 offered unique set of benefits. We elaborate using examples drawn from one graphic in each participant's curriculum:

P1's Latitude-Longitude Exercise:

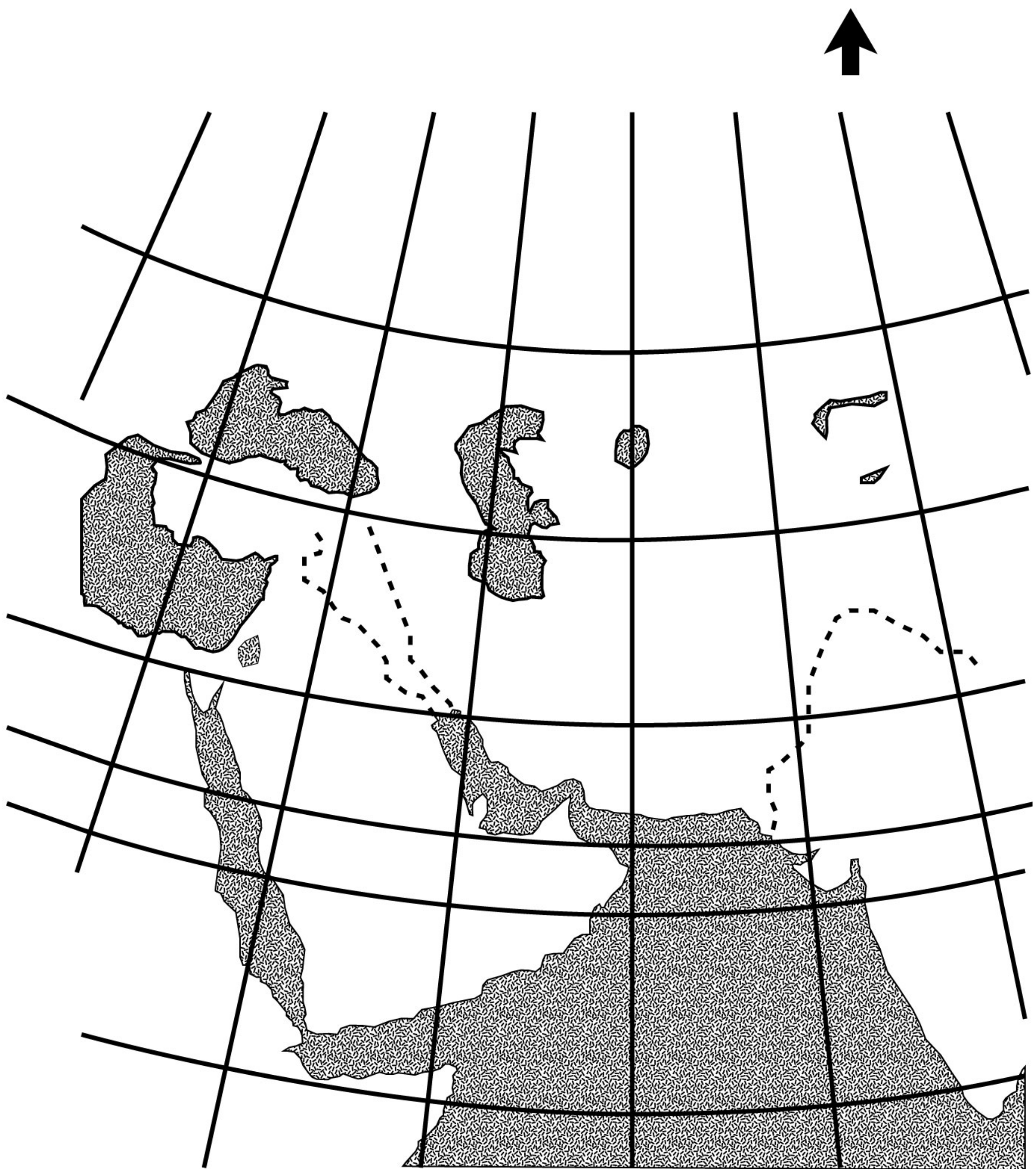


Figure 5.7: This T3 graphic of the middle east was produced for a latitude-longitude mapping exercise that S1 worked on in one of their classes. In this exercise, they were given a list of coordinates to mark on the map. S1 used the T3 graphic to retrieve the latitude and longitude and placed a tactile marker at the corresponding location of the listed coordinates in the activity.

We devised an exercise sheet for S1, involving the plotting of Middle Eastern cities and natural water bodies using latitude and longitude coordinates. This assignment was designed to follow a classroom lesson that introduced the concept of latitudes and longitudes using a tactile graphic labeled in braille. However, P1 reported that S1 encountered difficulties in comprehending the concept when exposed to the initial tactile graphic. Consequently, P1 viewed this as an opportunity for individualized instruction employing the T3 exercise graphic as part of an exercise , rather than regarding the tactile graphic as a hindrance. This personalized approach became imperative due to S1's recurrent struggles in grasping concepts within a classroom environment, necessitating supplementary review during independent study sessions.

> *"For S1, I think it was difficult (to interpret) just like in general. Because I feel like for somebody who's blind, latitude and longitude lines are invisible right? But for us, we see it. And then, as a whole, we see these latitude and longitude lines going across like a map and we get the overshot of it. We see it all in in one [...] so just just that in that kind of aspect it was kind of hard for S1 to like really understand and gauge, which that's more of a lesson, not a tactile graphic thing [...] they may have been thinking about something differently in class than what they saw on the exercise graphic".*

After receiving an explanation from P1, S1 successfully obtained the audio labels for the latitude and longitude lines by asking at the location. This enabled them to develop a strategy to complete the exercise independently and they were able to finish the exercises more quickly on the T3 tablet compared to using a tactile graphic.

> *"The T3 it helped for that, because they would hit it(latitude/longitude lines) just to make sure they were on the right one, follow it over. But then they would hit each intersecting line to make sure (to query for audio-label). So that way they didn't have to go up and read the braille up top. and then follow that line back down. That was another thing that could be really kind of cumbersome. And so they actually kind of figured that strategy out on S1 own. They would go over and then hit the line and followed it to the intersecting line, and then it announced what line they were at ... which was perfect. It really it worked out for her"*

In traditional tactile maps labeled with braille text, students typically needed to locate the braille coordinates at the termination of latitude and longitude lines and subsequently navigate back to the point of intersection. However, T3 graphics streamline this process by already providing audio labels co-located at the latitude and longitude grid lines, therefore eliminating the time-consuming steps of seeking braille labels at the outskirts of the sheet and then reorienting within the grid to add tactile markers as would be the case in braille-labeled version of this exercise sheet. This enhancement empowered S1 to autonomously determine the most efficient strategy for completing the plotting exercise, aligning with P1's educational objectives.

P2's Interactive Exploration of a Grocery Store Map

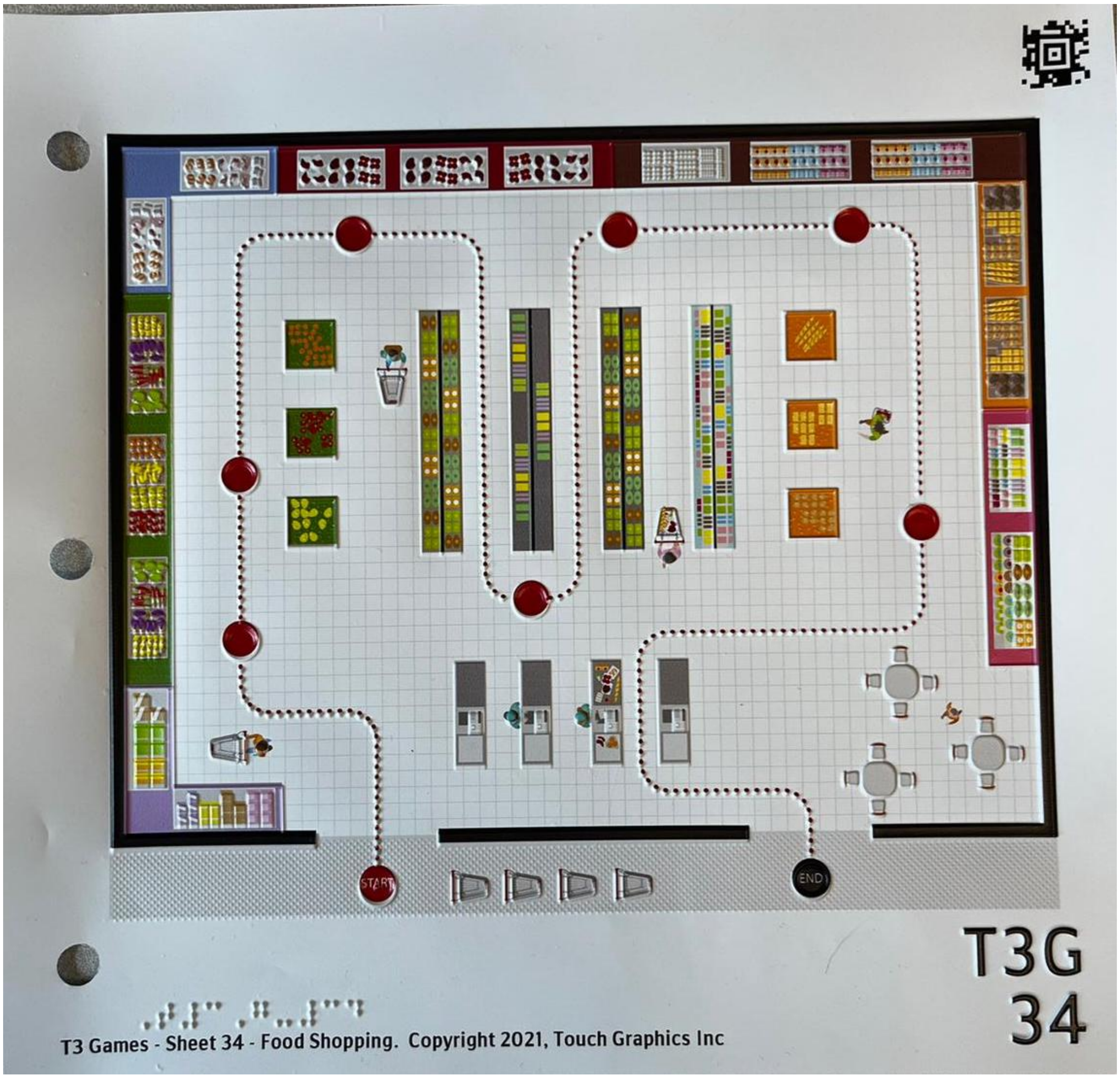


Figure 5.8: Practice sheet of the grocery store floor plan that is part of the T3 games starter pack. The sheet is programmed as a game where it asks users to first identify various parts of the grocery store represented in the sheet, such as the aisles, check-out counters, entry and exit doors, deli section etc. The reader is then asked to follow the marked route to answer the prompt for finding various items in a shopping list.

During the study, P2 incorporated an interactive tactile map game from the T3 starter pack as an additional practice exercise for their student. Although this specific map wasn't included in the official curriculum, P2's primary aim was to provide S2 with an opportunity to enhance their skills in reading different indoor maps.

The example sheet from the T3 starter pack was designed as a guided exercise, where T3 would deliver instructions to encourage the student to explore and point to various items within a grocery store setting. Subsequently, there was an exercise prompting the reader to "find x" and recording their correct responses. In essence, it offered a self-contained gamified approach to explore a tactile graphic.

> *"I put it on the T3, and then said - 'Okay, let's go through it and play the game now that you've explored it'... S2 ultimately got everything right. But then for D2 what it described as accuracy, I think, was like 83% or something. So they had to go back and do a couple of them over because they either got it wrong or didn't understand what the question was, but then got it the second or third time"*

P2 found the interactive tactile map game to be *"pretty effective as far as giving S2 an overview of the building"*. P2 appreciated the programmed prompted exploration in this interactive starter pack map. Although we did not produce any similar prompted exploration sheet during our deployment, P2's experience demonstrates the strong potential for similar exercises to enhance a student's understanding of maps and navigation.

The latitude-longitude exercise sheet and the gamified map exploration represent instances of intricate educational tasks facilitated by the use of the T3. These activities contribute significantly to the development of essential skills - ability to plot points on a grid and cultivating map knowledge through a systematic exploration process. While similar tasks can also be accomplished with braille-labeled tactile graphics, our participant TVIs acknowledged the value of T3 in providing students with greater autonomy and improving their task execution speed for these complex tasks.

5.5 Discussion

Our objectives from this deployment study with the T3 were:

- To identify the factors situated in workplaces of our participants that may affect initial adoption, and continued use of the T3 tablet in schools (RQ1).
- To establish practical audio-tactile graphic design guidelines based on realistic use cases where audio-tactile graphics are used for classroom tasks (RQ2).

- To understand the effectiveness of T3 graphics in supporting our participants achieve some of the educational outcomes which tactile graphics typically support (RQ3).

From our study, we learned about how the job roles of educators would change if they used T3 tablets for teaching. We investigated the prospects for adoption of T3 tablets based on factors known to influence the adoption of new media for presenting tactile graphics in schools (RQ1).

Based on the designs we produced for our participants throughout the deployment, we derived a set of preliminary design guidelines for T3-based audio-tactile graphics that are relevant to similar audio-tactile graphic systems (RQ2).

Lastly, our study serves as evidence that the T3 graphics supported various educational outcomes discussed by our TVI participants in two distinct use cases: geography classes and O&M exercises (RQ3).

When studying the use of novel assistive technology in the field, it is important to consider how the technology integrates with the larger ecosystem that supports its use. Our findings highlight the intricate relationship between our participants, their students, and the broader social environment that facilitates the use of T3 graphics. In this discussion, we will delve into two critical elements of this socio-technical coupling:

prospects for a *"Universal design" in learning* through the use of T3, and the necessity for audio-tactile graphic authoring tools

5.5.1 T3 in classrooms: "To me, this is like Universal Design"

Often, novice readers find it daunting to read tactile graphics without assistance from educators [218, 220, 217, 173]. Throughout our study, our participants noted that their students displayed greater independence when interpreting audio-tactile graphics on the T3 compared to braille-labeled tactile graphics. This increased autonomy stemmed from the co-located audio feedback on the tactile overlay, effectively minimizing the disorienting hand movements that are commonly associated with reading braille-labeled tactile graphics (ref Section 5.4.3.1). We also observed how S1 exhibited a swifter pace when interpreting graphics on the T3, as opposed to braille-based tactile graphics. Furthermore, P1 underscored the significance of the T3's interactivity in enhancing S1's classroom experience, emphasizing, *"cause that's how all other sighted kids are reading that graphic"*. We hypothesize that audio-tactile graphic systems like the T3 can potentially be used in schools in the future. Our participants not only reported significant interest from their students (ref Section 5.4.1) but also highlighted the importance of having systems that are similar to those used by sighted students, or even better, systems used by both sighted and blind students. This aligns with the findings reported by Baker et al., emphasizing the importance of such systems for adoption [16]. P1 also referred to the T3 as a *"universal design"* that allows sighted and blind students to collaborate using the same interface, unlike braille-labeled tactile graphic. Using the three principles of Universal Design for Learning (UDL) for students with disabilities in a mixed-ability classroom, as discussed by Hitchcock et al. [85], we can delve deeper into P1's assertions that the T3 represents a significant stride towards creating an inclusive classroom environment for students with visual impairments:

- **Principle 1 - Provide multiple means of presentation**: This concept encompasses the deployment of diverse media to convey information and bolster learning. Relying solely on one form of media might not cater to the needs of all learners across various tasks and instructions. T3 graphics embody this principle by enabling the conversion of printed information into tactile formats, complemented by the integration of braille and audio labeling. Consequently, graphics become accessible to students with visual impairments, while their sighted counterparts can engage with the printed details, discern lines and patterns visually, and benefit from auditory descriptions.

- **Principle 2 - Provide multiple means for students to express their knowledge**: This principle refers to offering various options for how students learn and demonstrate their knowledge. T3 graphics support this principle by being adaptable for multiple learning activities, such as quizzes and independent study, without placing a heavy burden on educators when adapting existing graphics for different purposes as we saw in this deployment study.

- **Principle 3 - Provide a variety of means of engagement**: This refers to providing students the ability to engage with the content in multiple ways because *"each student will engage with learning for different reasons and in different ways"*[85]. The T3 graphics were flexible for use in multiple settings and forms of engagement. Our participants used the T3 graphics in classroom settings, independent study rooms, outdoors for O&M tasks, and at home with assistance from parents.

In essence, looking at the T3 through the lens of UDL emphasizes that while tactile graphics serve as a means to make course content accessible to BVI students, devices like the T3 go a step further in fostering a classroom environment that is truly inclusive, enhancing the overall learning experience.

5.5.2 Design Guidelines and Authoring tools for Audio-Tactile graphics.

To advance the integration of audio-tactile graphics within educational contexts, there is a critical need for the development of authoring tools designed to create these graphics and the training of tactile graphic artists in their effective utilization within their current roles. Currently, there are no dedicated authoring tools available for the creation of audio-tactile graphics.

Tactile graphics have been produced using various tools previously explored, including Microsoft Word, CorelDRAWr [155], BrlGraphEditor [20], TGD Pro (Tactile Graphics Designer Pro) [54], and Tiger Designer [208]. These authoring tools offer tactile artists a range of options, thereby influencing the utilization of tactile graphics in educational settings. In our study, we adopted an ad-hoc approach and utilized the same tools employed by our participants for creating tactile graphics. Nevertheless, there is a need for a robust authoring tool explicitly tailored for audio-tactile graphics. While the assessment of the adoption and replication of our ad-hoc method in educational institutions was beyond the scope of our exploratory study, it remains an open question for future research efforts.

The design guidelines we present for audio-tactile graphics (see Sec 5.7) are derived from the creation of 29 graphics tailored for O&M and science classes. These graphics were exclusively employed for classroom instruction, independent study sessions, homework assignments, quizzes, and navigation exercises. We strongly advise adhering to these guidelines when generating graphics using PIAF sheets with dimensions measuring 11 inches by 11.5 inches.

Our design guidelines establish a sequence for creating audio-tactile graphics.

Step 1: First step, as discussed in Section 5.7.1, involves designing the tactile overlay. Our guidelines in this step are a modification of the design guidelines for tactile graphics recommended by the Braille Authority of North America (BANA) - which are widely used by transcribers to create tactile graphics in schools. Additionally, we incorporate Prescher et al's guidelines for contrasting tactile texture [165], and iconsets proposed by Ramsay et al. and [167] and Lobben [118]. Although existing guidelines are useful for braille labels, our modifications to these guidelines support audio-labels, specifically considering the design of interaction zones for audio labels such as recommended dimensions for tactile elements to improve touch-queries, spacing between adjacent tactile elements, etc.

Step 2: Following this, the next step is to set up interaction zones for each tactile element, each linked to an audio label. Detailed guidelines for interaction zones, including guidelines for improving accuracy of touch-queries and managing interaction zones for overlapping tactile elements, are provided in Section 5.7.2. These guidelines are based exclusively on designs from our study that effectively met our participants' instructional requirements when teaching their students, and haven't been discussed in prior literature.

Step 3: The final step involves strategically placing audio labels across various layers in a way that intuitively supports the graphic's intended task. In Section 5.7.3, we discuss how designers can effectively utilize introductory announcements, different layers of audio labels, and audio tones for effective information conveyance. For the audio-label interaction zones and corresponding audio-label design, we referred to Siu et al's guidelines for data narratives for accessible data visualizations [188], and Pandey et al's guidelines for tactile graphics with audio and braille labels [148].We adapted previous guidelines to tailor our designs as per our educators instructional activities like homework and independent study, and to enhance tactile exploration for novice readers of tactile graphics.

Additionally, our design decisions were influenced by insights from Study 2 discussing the co-design workshop for designing audio-tactile graphics with educators. Study 2 study served as a foundational step in aligning our approach with the established workflows of educators responsible for creating tactile graphics in school settings.

5.5.3 Tactile graphic or audio-tactile graphic?

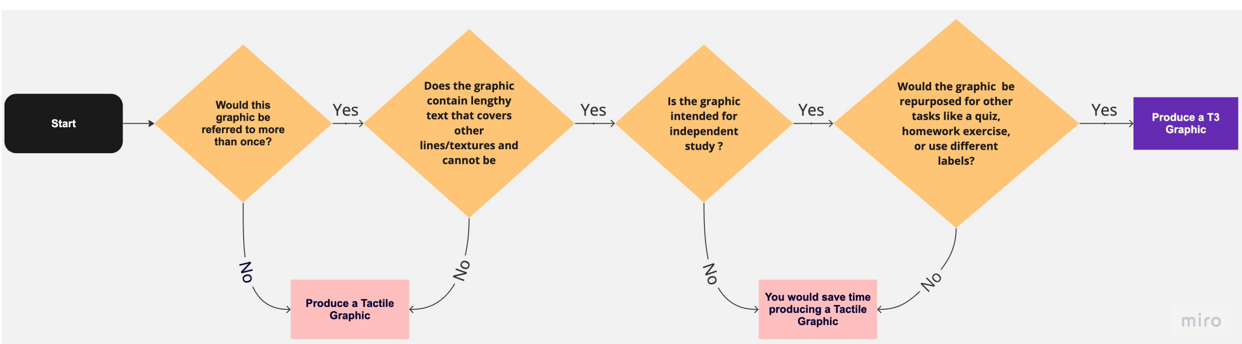


Figure 5.9: Flowchart of questions to consider when making the choice of whether to produce a tactile graphic or an audio-tactile graphic

It is important to understand that audio-tactile graphics should not be seen as a substitute for tactile graphics, but rather as an alternative for presenting certain graphics in a more effective way.

We suggest the following flowchart to outline the design-based factors that should be taken into account when deciding to use audio-tactile graphics instead of braille-labeled tactile graphics. This flowchart can be utilized similarly to the tactile graphic decision flowchart discussed in the BANA guidelines.[29].

5.5.4 Limitations of the Study

We acknowledge a few practical limitations of the T3 tablet itself that may affect its use. The T3 graphics require a significant lead time to produce tactile graphics compared to other quicker methods. This makes it less desirable in situations where TVIs are not given enough lead time from classroom teachers to design graphics. In these situations, TVIs choose to create their own tactile graphics to meet the swift turnaround time instead of relying on the T3 graphic artist to design an audio-tactile graphic.

Furthermore, the T3 tablet is not portable, which makes it less usable than braille-labeled tactile graphics for navigation exercises under O&M training.

Although the current version of the T3 tablet provides the highest resolution for audio-accompanied tactile overlay systems, we encountered several bugs and glitches that made it less usable, especially in situations where higher reliability is required, such as exams.

The T3 tablet is well-suited for presenting complex graphical information due to its layered audio-labels. However, for simpler graphics with fewer details, educators may find it easier to use other tactile media that take less time to produce, such as Wikki Stix, draftsman tactile graphing sheets, or an embosser.

These limitations indicate that audio-tactile graphics may not be useful for all tasks supported by tactile graphics. It is important to acknowledge this distinction in future research when selecting tasks to evaluate audio-tactile systems. Researchers should avoid evaluating systems for tasks and contexts that inherently undermine the value of audio-tactile graphics.

5.6 Conclusion

For this deployment study, we structured our research questions around the following overarching objectives:

- **Understanding Initial Adoption**: We sought to investigate how educators can effectively integrate devices like the T3 into their educational environments.
- **Understanding Practical Audio-Tactile Graphic Designs**: Our aim was to develop a set of practical design guidelines for audio-tactile graphics that are grounded in the context of educational use.
- **Understanding Whether T3 Graphics Support Educational Outcomes**: We sought to understand whether the T3, and audio-tactile graphics we produced, aided educators in achieving their educational objectives.

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Through our deployment study, we make valuable contributions to the understanding of the design landscape for audio-tactile graphics in educational settings. We contribute practical design guidelines tailored for audio-tactile graphics employed within classrooms and demonstrate a grounded methodology for comprehending how situational factors influence the successful integration of a novel access technology through field deployment and embedded data collection.

5.7 T3 Graphic Design Guidelines

5.7.1 Step 1: Designing Tactile Overlay

When designing audio-tactile graphic, we recommend starting with the design of the tactile overlay.

5.7.1.1 Steps For Designing Tactile Overlays

Tactile overlays should be designed primarily following the Braille Authority of North America's Planning and Editing Steps Unit 3 [29]. The summary of these steps are:

1. **Define primary Elements**: Categorize the information in the print graphic that needs to be included in the tactile graphic into primary elements: Area, Line, Tactile Symbols, and Label.

2. **Editing Image Content**: When creating a tactile graphic, it is important for the designer to maintain the content and meaning of the original diagram and include additional detail to convey the meaning better if needed. The purpose and use case of the graphic should be determined by consulting with a TVI or classroom teacher. It is recommended that a single graphic should have no more than five different area textures, five different line styles, and five different types of tactile symbols.

3. **Planning**: Document the steps taken to transcribe a graphic such as listing the meaning of different textures and line patterns, information associated with the key, details excluded from the source image, separations in the image, division of a graphic in separate images etc.

   Include a summary of planning details as a note, as part of the introductory announcement that is played at the beginning when the tactile overlay boots up.

4. **Planning Size and Layout**: Consider the size of the sheet available, amount of detail to add, spacing between distinct queryable tactile elements (see Spacing section) when choosing the amount of detail to include.

5. **Elimination and Offloading**: Based on step 2, 3, and 4, eliminate details from the print graphic. You may choose to divide up the graphic in multiple parts or offload some of the details over to audiolabel. Note: the details of content eliminated from print version should ideally be included as an audiolabel announced in the beginning when the tactile overlay boots up.

5.7.1.2 Tactile Elements Sizing And Spacing

It is important to consider the size and spacing of the tactile elements on the overlay to ensure ease of interpretation for readers, as well as to support interaction and exploration gestures on the T3 device. In order to meet our specific requirements for the T3, we have modified the general guidelines for sizing and spacing of tactile elements recommended by the Braille Authority of North America.

- **Areas**. Minimum size 1/4 square inch (6 square millimeters). Very small areas are more easily read if marked with a pattern, and boundaries are raised above other areas to increase the tactual contrast or shown below another area that is raised. Refer to the recommended tactile patterns in the Tactile Pattern Contrast section for guidance on selecting patterns with ideal contrast when placed adjacent to one another.

- **Lines**. Primary lines must be minimum 1/2 inch (1.25 centimeters) in length.

- **Dashed Primary Lines**. The length of each dash should be 1/4 to 3/8 inch (6 millimeters to 1 centimeter), separated by spaces approximately half the length of the dash.

- **Secondary Lines**. For tick marks on number lines and graphs, the length must be 1/2 inch (1.25 centimeters) or 1/4 inch (6 millimeters) on each side of line and shown as less significant than primary lines on the tactile graphic.

- **Lead lines**: They connect tactile elements to symbol or braille labels. must be the least significant line in the graphic, with a preferred minimum length of 3/4 inch (2 centimeters) and a preferred maximum length of 1-1/2 inches (3.75 centimeters), with no arrowhead at the end. If at all possible, a lead line should be straight.

    - One end of the lead line should touch the element it identifies and the other end should be at least 1/8 inch (3 millimeters) from the beginning or end of the braille label.

- **Arrows**: An arrow should consist of a shaft and either a long solid triangle. The shaft may be solid or dashed, but both the shaft and arrowhead should be of approximately the same weight. The arrowhead should be isosceles (with two sides of the same length) and have an angle between the two longer sides between 30º and 45º to best indicate direction.

- **Tactile Symbols**: To discriminate between two or more different-shaped symbols, the minimum diameter must be at least 1/4 inch (6 millimeters). The space between a point symbol and any other element must be a minimum of 1/8 inch (3 millimeters).

- **Braille Labels**: Labels must be placed at a minimum distance of 1/8 inch (3 millimeters) and a maximum distance of 1/4 inch (6 millimeters) from any other elements. If it is not possible to place the label within this range, it must be placed far enough away to allow for a 3/4 inch (2 centimeter) lead line.

    - If you choose to include braille labels along with tactile labels, consider making the braille lables queryable.

- **Tactile Pattern Contrast**: When placing tactile patterns close to each other, it is important to consider whether tactile patterns adjacent to one another have sufficient contrast. Since all tactile elements also function as audiolabel-query-zones, it is important to communicate separation between adjacent areas associated with distinct audiolabels (ref fig 5.10).

- **Lead Lines and Tactile Symbol Icon set**: A lead line is typically a fine line that connects a braille label or key symbol to the object or feature it identifies. One may also choose to use a lead line between a small area that may be hard to query and a tactile symbol that can be queried for an audio label associated with the small area. Use following recommended designs for tactile icons and lead-lines (ref fig 5.11):

- **Tactile stickers or marker recommendations**:

    - Any modifications made to the tactile overlay using stickers or braille markers should also accompany changes to the query-zones and audio labels.

    - Use conductive markers that do not obstruct touch input for querying audiolabels.

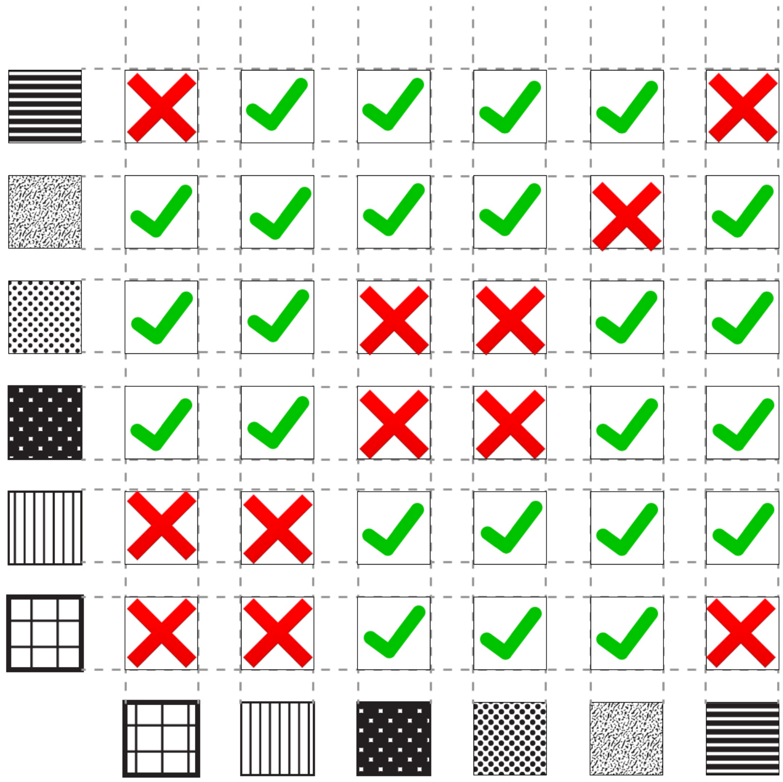

Figure 5.10: Prescher et al's scale of contrasting textures, adopted to include only those which are common between Prescher et al's [165] and Lobben's [118] recommended set of tactile textures.

5.7.2 Step 2: Defining Audiolabel-Query-Zones

Once we have the design for the tactile overlay, we can then create interaction zones to query audio-labels associated with a tactile element.

- **Buffer Zones**: Consider implementing buffer zones to ensure accurate access to each element. A buffer zone would account for the width of a fingertip, allowing users to query for a tactile element by pressing on the border surrounding it. For instance, when defining the query zone for a rectangle with dimensions of 1 inch X 2 inches, one may define it as a rectangle with dimensions of 1.1 inches X 2.1 inches. However, the dimensions may vary depending on surrounding elements.
  - When defining query zones for two tactile elements of equal priority, place the querying zones beneath the border lines without any buffer for the greatest accuracy.

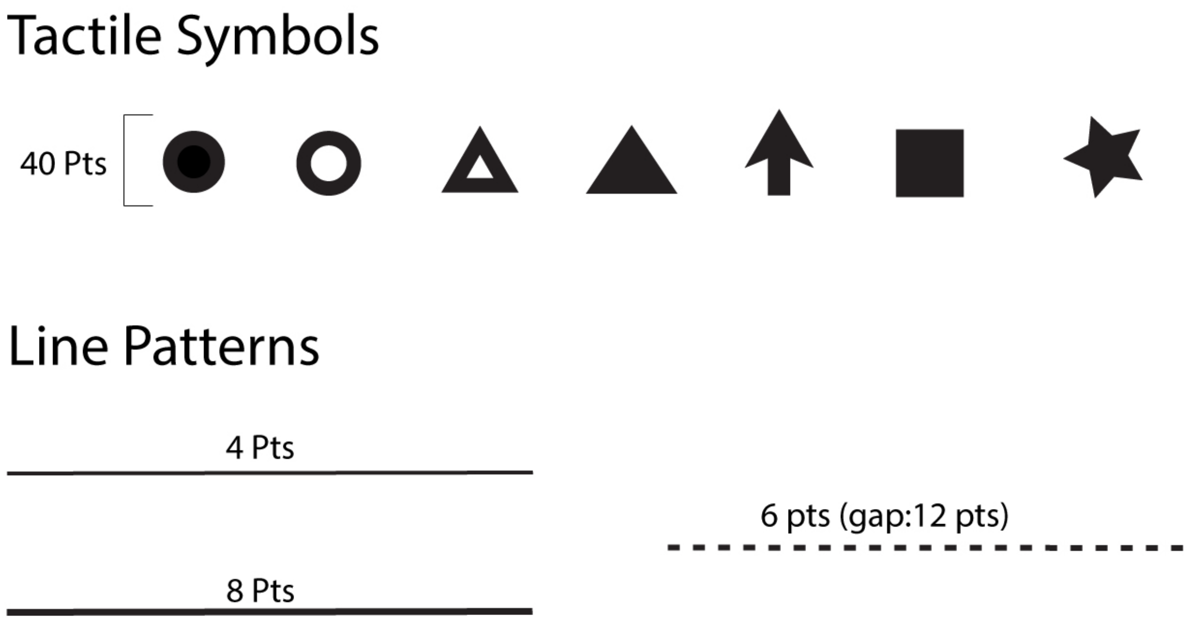

Figure 5.11: Icon set for tactile icons and lines that we used with our T3 graphics. These are borrowed from the icon set proposed by Ramsamy-Iranah et al. and [167] and Lobben [118]

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- When defining the query zone for a tactile element adjacent to another element of lower priority, expand the buffer zone accordingly.
- When dealing with overlapping tactile elements, one audio label-query-zone should take priority over the others. Designers should remember this prioritization in mind when choosing to include overlapping tactile elements.

- **Thoroughness in Labeling Tactile Elements**: To promote easy interpretation, assign interaction zones and audio-labels to as many tactile elements on the tactile overlay as possible. This means that all tactile elements on the overlay can be queried to ensure accuracy in interpretation, and orientation within the graphic.

5.7.3 Step 3: Adding Audio Labels

We recommend authors to consider the context of the intended task when writing audio labels for graphics. This is especially important when adding audio labels that are embedded in layers. Recommendations for audio labels are from previous studies on audio-supported tactile graphics [148, 135, 88, 188, 65].

- **Avoid verbose audio announcements**: To improve clarity, avoid using overly long audio announcements. Instead, consider breaking the text into multiple layers of audio announcements to organize them hierarchically. Please refer to the guidelines below for structuring audio labels.

- **Avoid visual metaphors**: Avoid using language that relies on visual identifiers when referring to elements such as their color or statements such as - such as "this/that/over here/over there". Instead, use descriptive language that relates to spatial awareness and tactile exploration. For example, describe line and area textures, or describe the location of another marker in relation to the current marker.

- **Avoid simultaneous announcements**: To ensure that readers do not miss important information, it is recommended to avoid simultaneous audio announcements and tones. This can be accomplished by designing interactions in a way that prevents simultaneous querying of multiple audio labels, and by avoiding the overlap of details such as tones and announcements.

- **Audio-labels for all tactile elements**: It is important to ensure that all tactile markers, such as areas, lines, symbols, and braille labels, are accompanied by corresponding audio labels. These tactile markers serve as landmarks for orientation, so labeling them is crucial.

- **Introductory Announcements**:The introductory announcement should provide context for the graphic and give an overview of its content. It should include significant items to look for, overall trends (for graphs or charts), the location of key elements such as axes and a north pointing arrow, and any additional information typically included as a transcriber's note. The purpose of the announcement is to help the reader become familiar with the graphic before exploring it.

  - Summarize the exact takeaways from the graphic and highlight any important numerical values. Additionally, mention the total number of important elements that a reader needs to find in the graphic.

  - Standardizing a template for framing introductory announcements helps create a consistent and familiar experience over time. The template should include content, context, sequencing details, and more.

- **Structuring the Audio labels** : Designers should organize information across the various layers of audio-labels as per a hierarchy that complements the task supported by the graphic.

  - Organize information across layers of audio labels in a way that allows for easy skimming through the graphic, while also enabling detailed study. Prioritize critical details for understanding the graphic at the surface level, and include additional details in subsequent layers.
  - For time series-based graphics or chronological data points, audio labels can be used to describe where to look for the next marker. These labels should be written with reference to their current location.
  - Information that would typically be part of a key could be included as a layer for the audio label. For example, describing the information that is embedded as an area texture, line pattern, or a tactile symbol.

- If you choose to include abbreviated braille labels in addition to audio labels, ensure that the audio labels are used to explain any abbreviations.

- Consider providing a list of Braille labels for items in addition to the audio-tactile graphic. This is particularly useful when the objective of the graphic is to communicate textual details, such as spellings of words, that may not be clear in audio announcements.

5.8 Summary of the Chapter

This chapter presents the concluding study of this dissertation, where we built upon our initial reactions to the T3 tablet garnered during the co-design workshop simulations. The study aimed to investigate how audio-tactile graphics can be integrated with existing design practices and instructional strategies, and how effectively they can contribute to teaching objectives within a school context. For this research, we equipped two Teachers of the Visually Impaired (TVIs) with T3 tablets to be incorporated into their instructional repertoire with a selected student who possessed the prerequisite skills for reading audio-tactile graphics. Over a six-week period, I supported the TVIs in converting source images into audio-tactile graphics, essentially performing the role of a T3 graphic artist. The participants had predefined educational goals and reported achieving many of them through the use of T3 graphics. For example, they noted successes in fostering student autonomy in navigating complex tactile graphics, offering a level of graphic detail comparable to what sighted students access, and enabling visually impaired students to keep pace with their sighted peers in classroom reading activities.

However, there were anticipated educational outcomes that the T3 did not significantly support. These included the device not saving significant teaching time for simpler concepts that could be addressed with quicker prototyping tools, its cumbersome form factor limiting its portability for student use between home and classroom, and the necessity for parental assistance.

Throughout the deployment, the T3 proved compatible with various teaching strategies and classroom activities where tactile graphics are traditionally employed. My role as a T3 graphic artist met the participants' workflow expectations and turnaround times. The study identified specific scenarios in which educators preferred the T3 over other alternatives, highlighting the device's strengths.

Our investigation underscores the necessity for a robust audio-tactile authoring tool that would enable educators to undertake the role of a T3 graphic artist and create their own graphics within their work environments. When placed within the broader classroom ecosystem, the T3 displayed the potential for such tools to facilitate interactions between BVI students and their sighted peers during inclusive classroom activities.

The findings contribute to the broader discourse on designing audio-tactile graphics, proposing recommendations for tactile stickers compatible with modifications of tactile overlays. We also suggest that study designs evaluating audio-tactile graphics in educational settings take into account the influence of the surrounding ecosystem to ascertain factors that affect the long-term sustainable usage of these devices.

CHAPTER 6

Discussion

My thesis argues that **there are three primary stakeholders who play pivotal roles in influencing the design and sustained utilization of audio-tactile graphics systems within educational institutions- educators of visually impaired students, classroom teachers, and the end users (i.e., BVI students). Consequently, the design of the audio-tactile graphics system should be thoughtfully tailored to acknowledge the needs of all the stakeholders involved and the workflows which facilitate its integration in school settings. From a comprehensive viewpoint, audio-tactile graphics systems emerge not just as tools that improve image access for BVI students, but also as a catalysts for exploring innovative pedagogies and aiding educators in achieving specific educational milestones.** Here, ”pedagogy” refers to the instructional strategy for teaching both the skill of reading tactile graphics and the delivery of course content using a given tactile graphic.

My research contributes to the broader discourse within HCI research on utilizing audio and tactile media to enhance image accessibility for BVI readers and educational assistive technology. Existing research in this space that looks at educational contexts has primarily focused on the early developmental stages of access technologies that support image accessibility [48, 141, 94] . Among the studies examining more advanced iterations of access technologies, the perspective has predominantly centered on students [6, 24, 159]. Nevertheless, it is important to recognize that the practical aspects influencing the widespread adoption of new access technologies come into play when observing educators who facilitate the use of such technology. This becomes even more pertinent over an extended period, once educators have devised pedagogical methods that seamlessly integrate an access technology into the broader learning ecosystem [203, 36, 47, 193]. My research effectively positions itself in the later stages of the access technology development process. It involves the simulation of how educators seamlessly integrate the audio-tactile graphics T3 - a commercially available audio-tactile learning platform, into their existing educational ecosystems, which already accommodate the use of braille-labeled tactile graphics in a classroom.

Throughout all three studies, my focus lies on the workflows of educators when they create and utilize tactile graphics in their teaching practices. In these studies, the development of the T3 workflow is built upon the collaborative structures that support the incorporation of tactile graphics in classrooms. This approach leverages an existing educational ecosystem during participatory investigations aimed at understanding how the T3 tablet can assist educators in achieving their educational objectives.

The study of educator workflows was facilitated by a shared assumption that the T3 device and the T3 graphic designs are sufficiently user-friendly for BVI readers. This assumption is rooted in my adherence to guidelines for audio-tactile graphics, which have been recommended in prior research involving BVI readers[147, 79, 82, 125, 123, 148]. Additionally, earlier studies have examined the effectiveness of audio-tactile graphics on the T3 device with BVI readers[135, 112]. Given the positive response received from TVIs in study 3, it is reasonable to assert that my assumptions regarding the effectiveness of the T3 device and our audio-tactile designs were indeed valid.

In previous HCI literature, the process of transcribing tactile graphics has conventionally been viewed as a standardized procedure, often considered in isolation from the specific contextual factors in which transcribers operate [111, 164, 60, 213, 214, 35, 26]. Consequently, only a few studies examining the transcription process or the development of tools for automating tactile graphics creation have delved into the contextual settings in which these processes are deployed[93].

In study 1, I explored the intricacies of the tactile graphics transcription process in educational settings. This investigation included conducting interviews with a range of stakeholders to gain insights into their experiences with the creation and application of tactile graphics in their respective learning environments. I found that the steps followed by these stakeholders exhibited unique variations, contingent upon whether they worked in schools or in transcription agencies. In my research, I introduced **a modification to steps that are typically considered in transcriptions** that include:a)obtain well-formatted source files from clients, b)education, i.e. creating accessibility awareness among external stakeholders, and c)student feedback integration. This revised definition of the transcription workflow is particularly relevant for studies focused on evaluating tools designed specifically for use in educational institutions.

In my second study, I examined how educators utilized the tools currently at their disposal for producing audio-tactile graphics within their work environments. I specifically focused on their established workflows and collaborations when transitioning to the creation of audio-tactile graphics. Notably, it is not uncommon in participatory research to engage with stakeholders who may not have disabilities but hold essential roles in the process, as was the case with transcription specialists in my study [122, 153, 98, 97].

By focusing my investigation on the workflows of educators and how they can facilitate the creation of audio-tactile graphics, I examined the feasibility of producing T3 graphics in schools while adhering to the existing workflows with a caveat that participants received some assistance from researchers. During the workshop, it became evident that **a set of additional steps were necessary, extending beyond those required for tactile graphics creation**. My workshop however prompted discussions among participants regarding the potential for designing audio-tactile graphics that could empower novice readers to achieve greater independence without extensive assistance from TVIs or para-educators.

A central question emerged: Was the added effort involved in transcribing audio-tactile graphics justified by the anticipated outcome that T3 could enhance students' independence when reading tactile graphics? This hypothesis however could not be confirmed during the co-design workshop.

In my final study, I aimed to scrutinize the assumption emerging from Study 2 that the T3 device could indeed foster autonomy among students when reading tactile graphics, as part of a broader set of educational goals discussed by participants. During the deployment, I implemented an ad-hoc workflow aimed at supporting the creation and use of T3 graphics within educational settings. I demonstrated an approach to teaching with audio-tactile graphics that can effectively achieve various educational outcomes for TVIs, including **promotion of autonomy among novice readers of tactile graphics**. I argue that with the implementation of **a robust authoring tool for generating audio-tactile graphics**, we have the capacity to introduce audio-tactile graphics into schools where the conventional practice involves teaching with braille-labeled tactile graphics. In doing so, I contribute to the ongoing dialogue surrounding the adoption of innovative access technologies that, in theory, should be accessible to blind readers. However, in practice, their full realization is hindered by infrastructural limitations. In this context, "infrastructure" refers to the absence of a comprehensive ecosystem that can effectively support the creation and instruction of audio-tactile graphics.

My dissertation research has followed an exploratory path, with the primary objective of understanding how audio-tactile graphics can function within the established practices for producing tactile graphics within educational settings. This enabled my studies to observe the use of audio-tactile graphics within a workflow which can sustainably support their use in schools in the future.

In the subsequent sections, I delve into how the findings from my research contribute to the continuous endeavors in the realm of novel access technology development. Additionally, I shed light on the potential future of audio-tactile graphics in education and the far-reaching implications of integrating AI and LLMs (Large Language Models) in the endeavor to make visual content more accessible to individuals with disabilities.

6.1 Image-access in education: Patchwork of assistive technologies.

The T3 is one of several tools that blind and visually impaired individuals can use to access image content. Other tools include braille embossers, swell papers, tactile sketch boards (such as the Draftsman by APH), refreshable braille displays, and alternative text descriptions of images. I use the term ”image-access technologies” to refer to the sub-category of these assistive technologies.

In an essay on the rise of the term “end-to-end” used to describe the internet since the 1970s, Gillsipie explains that “every technology is shaped by a process of social definition, in which those invested in it struggle not only to implement the technology, but also to narrate what it is and what it is for” through ongoing processes of negotiations. [70] This quote illustrates how the term “internet” has evolved over time, from referring to the technological artifact itself when it was first coined, to now referring to the medium which enables communication and information consumption. The term ”internet” has evolved due to innovations that leveraged the Internet technology to produce products, services, and experiences far beyond what the original creators had envisioned when they first coined the term.

I argue that tactile and audio image-access technologies, T3 included, are currently undergoing this transformative phase of societal definition. The integration of these technologies is reshaping default standards of presenting graphical information through touch and audio. For example, the advent of embossing tools and design standards for tactile graphics has popularized tactile feature maps in national parks and monuments. Anti-discrimination legislation has paved the way for audio descriptions to become a staple for online streaming platforms, theaters and cinemas. Furthermore, advancements in computer vision and machine learning have given rise to services specializing in automated tactile graphics transcription, notably TMAP [135]. In this evolving landscape, when considering the overall utilization of image-access technologies, it’s imperative to view innovative tools not as isolated entities but within the broader context of their interaction and integration with other such tools. Thus, my research doesn’t simply focus on the T3 in isolation; instead, I examine its role and functionality alongside other image-access technologies that are simultaneously transforming the ways in which images are accessed and interpreted. Throughout my research, my primary objective has been to understand how the integration and application of various image-access technologies, along with the associated workflows, can influence and potentially redefine the role of the T3 within educational environments.

In chapter 2, we discuss how to capture the social and environmental factors which influence the utilization of an assistive technology, previous research in occupational therapy often refers to the Person-Environment-Occupation (PEO) framework [114]. The PEO model helps assess and address an individual's ability to engage in meaningful activities within their environment using specific technology. During the field deployment in Study 3, participants used various image-access technologies, including the T3, to create an inclusive education environment for their students. In case of the T3, ”environment” factors includes the concurrent use of other image-access technologies along with the T3, as these significantly influenced the contextual landscape in which T3 operated. For BVI students, it is common to use multiple image-access technologies together to address the challenges posed by a visually-oriented education system [16, 224]. By broadening the definition of the environment to include the presence of other assistive technologies, we gain insights into how educators can strategically utilize different image access technologies to bridge the gap between individuals' abilities and their desired activities.

I illustrate PEO model for T3 in education context in figure 6.1 which acknowledges the coexistence of different image-access technologies that cater to the diverse needs of educators and students. Each image access technology caters to specific use cases and necessitates unique supporting workflows. These workflows are interdependent and must be acknowledged to fully comprehend how image access technologies used alongside the T3 collectively enhance the support provided to educators and students. By adopting this holistic approach, my work acknowledges existing workflows and image-access technologies when studying a novel assistive technology. Although the influence of other assistive technologies on the selection of tasks for the T3 usage was not comprehensively captured, it is evident that our transcription and pre-teaching workflows were shaped by those established for traditional tactile graphics. The scant details concerning how alternative image access technologies impact the decision to represent certain graphics via the T3, as opposed to others, remains an open question for future research.

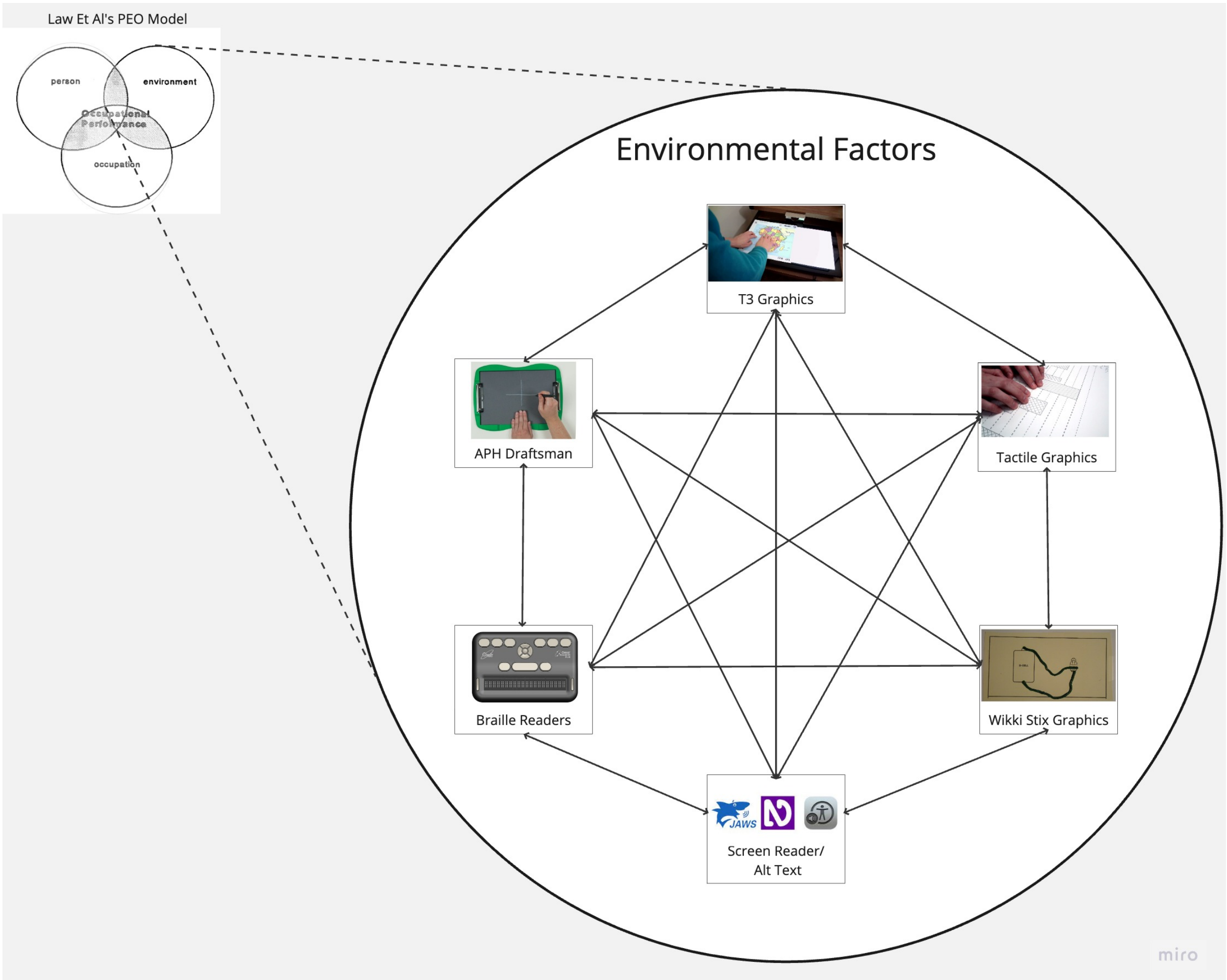

Figure 6.1: Image of the adaptation of Law et Al's PEO model where environment should include ways in which T3 interacts with other assistive technologies used

6.2 T3 TPACK: Measuring long-term adoption of the T3

The Technological Pedagogical Content Knowledge framework, commonly referred to as TPACK, is an established framework in the education-technology (ed-tech) space to capture the comprehension and integration of a technology into teaching and learning.

In study 3, I delve into factors that influence the adoption of the T3 from the perspectives of educators and previous research on the use of tactile graphics in classrooms. To holistically gauge the integration of T3 graphics within an educational institution, it is essential to develop a TPACK. As defined by Kohler, the development of a TPACK is a multi-generational process that involves cultivating a deeper understanding of the intricate relationships among

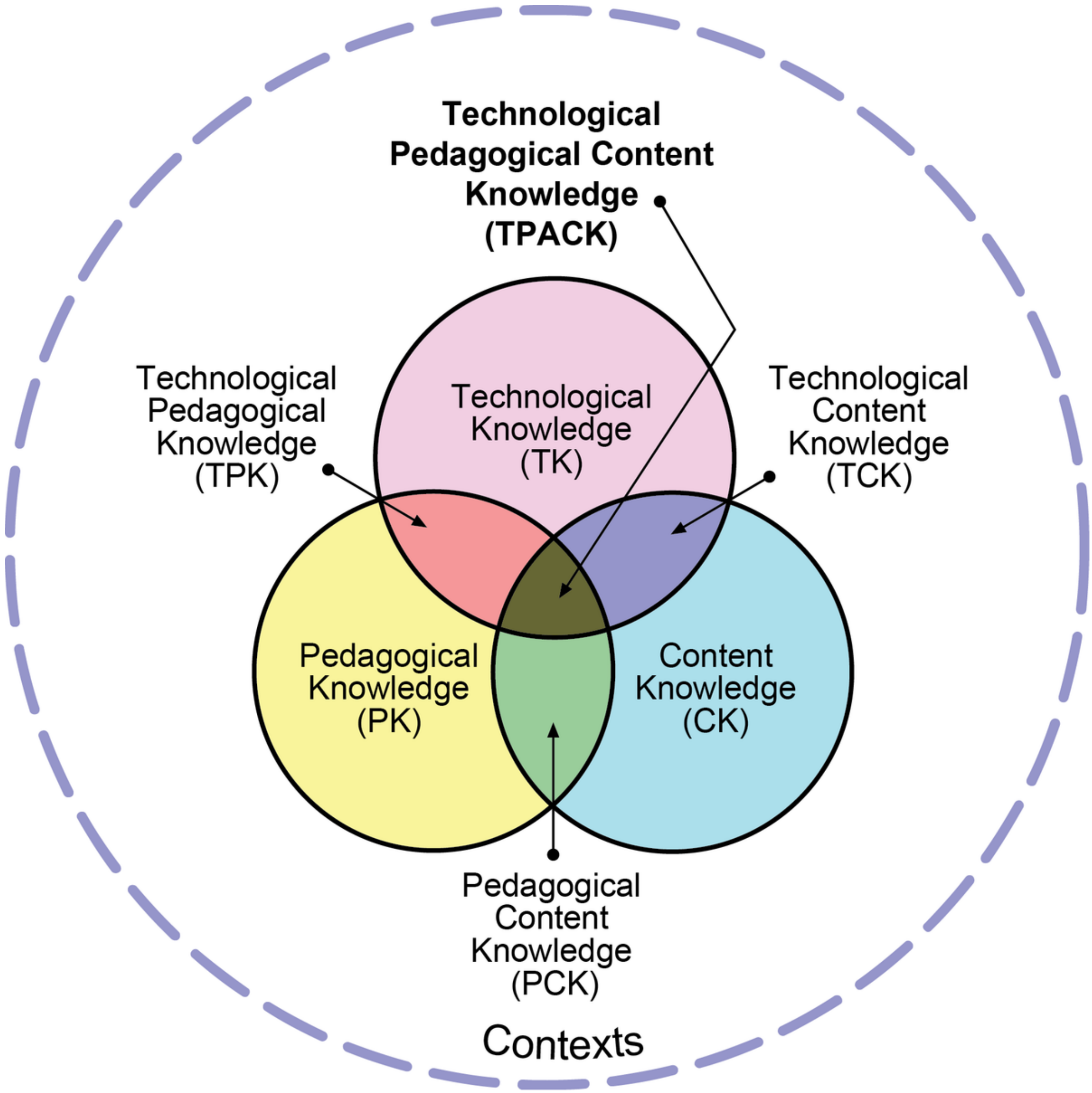

Figure 6.2: Image of TPACK

content, pedagogy, technology, and the contexts in which they together operate [103, 105]. My work contributes to the broader initiative of developing a more profound understanding of the interplay between audio-tactile graphics tools like the T3 (Technology), effective teaching methodologies using the T3 in educational contexts (Pedagogy), and comprehensive design guidelines for audio-tactile graphics and authoring tools for creating such graphics (Content). In essence, my research acts as a starting point for to the development of a TPACK model specifically tailored for T3 tablets.

Through the lens of Benton-Borghi's Universal Design for Learning (UDL) Infused TPACK [21], which seeks to incorporate assistive technology in the definition of technology, I unpack the insights I gained regarding the T3 across my studies:

6.2.1 UDL-infused Pedagogical Content Knowledge (PCK) for T3

"UDL infused PCK requires multiple options (using technology) for representation of the content, expression, or assessment (formative) of student's knowledge of content and engagement in the content". [21]

In studies 2 and 3, our TVI participants emphasized how the T3 would serve as an option alongside other methods for presenting graphical content, rather than replacing existing methods. Furthermore, in Study 3, the T3 introduced new avenues for students to interact with content but through interaction techniques that were familiar to the participants due to their experience with other assistive technologies. This resulted in a learning experience that sometimes aligned with how their sighted peers were learning. The innovative pedagogical content knowledge exhibited by our participants in these studies suggests the existence of a unique PCK for the T3 that is distinct from that of other assistive technologies with which our participants were acquainted.

To attain a better understanding of UDL-infused Pedagogical Content Knowledge for T3, it is imperative to deepen our understanding of the pedagogies that T3 can accommodate and the ways in which a student can engage with T3 content. Additionally, developing a comprehensive training plan is crucial to acquaint teachers with the T3 and empower them to select it when deemed necessary among other image access technologies.

6.2.2 UDL infused Technological Content Knowledge (TCK) for T3

"UDL principles require that teachers have technological knowledge of all(including assistive) technology that provides access to content and enhances student learning". [21]

The overarching objective of developing Technological Content Knowledge (TCK) is to comprehend or research which available technology is suitable for addressing challenges (offering varying levels of technology) and providing access (integrating instructional and assistive technology) for all students, including aspects of input, output, and engagement tailored to the specific content being taught.

My deployment study provides a limited glimpse into what this might entail if educators had access to the T3, enabling them to design content that caters to students' diverse engagement styles, including options like braille vs. audio labels, guided exploration prompts vs. autonomous exploration. A more extended deployment of the T3 would be necessary to gain a comprehensive understanding of how it can serve as a medium for sharing, engaging, and sparking further learning in school environments.

It is essential to note that authoring tools for audio-tactile graphics also fall under the purview of 'Technology'. In studies 2 and 3, I employ an ad-hoc process for authoring audio-tactile graphics. However, this approach only allowed me to capture the ways in which participating TVIs engaged in modifying the audio labels and tactile overlays of graphics that I produced for them.

The scarcity of robust authoring tools significantly restricts educators' ability to develop technological and content knowledge related to audio-tactile graphics systems [201]. Previous studies have proposed a number of approaches to authoring tools that have been evaluated with educators. For instance: Thevin et al's Spatial Augmented Reality tool for authoring audio-tactile graphics was tested with 28 participants during a classroom instruction study, the TGA helper uses a GUI based annotation tool to add audio-labels to exiting tactile graphics in a lab study with 3 visually impaired university students [201]. These studies demonstrate unique tools for designing audio-tactile graphics which require significant effort on the part of educators to learn and master the workflow for producing them. To foster proficiency in TCK for the audio-tactile graphics systems such as the T3, it is imperative to develop a robust authoring tool that can empower educators to create their own audio-tactile graphics effectively.

6.2.3 UDL infused Technological Pedagogical Knowledge (TPK) for T3

"Pedagogical knowledge supports the teacher's instructional decision-making concerning delivery models. These pedagogical decisions intersect with technological knowledge empowering the teacher to choose wisely among the myriad of technological options available". [21]

In study 3, we observed variations in the experiences of participants when using the T3, which were influenced by whether the content was related to Geography or O&M. We found that our participants engaged with tactile graphics and other assistive technologies for subjects outside of Geography and O&M, in for which they did not use the T3 Furthermore, where they did use the T3, they employed the system for a range of activities, including homework, classroom tasks, group work, and navigation exercises. These diverse use cases presented both opportunities and limitations for a device like the T3.

To harness the full potential of devices like the T3, there is a need for continued efforts in developing a comprehensive set of instructional strategies that align with the capabilities of such technology. In mixed-ability classrooms, educators may also have to explore pedagogical approaches that bridge the Technological Pedagogical Knowledge (TPK) gap between sighted and blind students, ensuring equitable learning experiences for all.

6.3 Automated transcription, AI supported access and the roles of educators and blind creators.

Automation in the realm of tactile graphics creation is of paramount importance, particularly given the time-consuming nature of the process, the importance of personalization based on readers' skills, and the shortage of transcribers. This scarcity often makes it challenging for individuals with visual impairments to access timely and tailored tactile materials, further emphasizing the need for efficient and adaptive automated solutions. Automation to improve image access however need not always mean transcription of tactile graphics, and can often take the form of text based description of images such as summary of a graph or chart [132, 139, 121], automatic alt-text and video-description generation [23, 144, 11]. With the emergence of large language models, tools such as GPT-4 [13], and mini-gpt[225] have emerged as a tool that allows users to interact with images through text based prompts to ask questions about the image or access specific information within an image. The challenge of automatically translating visual images into tactile graphics, paired with text that conveys their inherent semantics, has been tackled across various branches of accessibility research. These efforts span disciplines such as computer vision, machine learning, and the use of audio-haptic devices. Goncu, in his approach to automating the transcription of graphs, raises a pivotal question: "After extracting the syntax, semantics, and pragmatics of a diagram from its original visual form, what then constitutes an effective alternative presentation of an accessible diagram considering the diagram type, users, tasks, devices, and presentation media?" [74]. In response to this, I argue that the T3, with its capability to present information in both audio and tactile modalities, stands as a potential answer to Goncu's inquiry.

Goncu's research unveils a data storage framework designed to meticulously encode vital components of a graph, such as data points, employed patterns, labels, and similar relevant details about a graphic [74]. In the Tactile Chart Tool - a practical demonstration of this framework by Goncu, the chart information, consolidated in a text file format, is used to generate a tactile chart instead of using the source image file. In Study 2 and 3, while adhering to the T3 Task Flow, my role as a T3 graphic artist involved manually extracting intricate details from graphics using tools such as Adobe Illustrator. I then meticulously documented these data points in a spreadsheet. Goncu's framework, which aims at systematizing this extraction and storage process, mirrors an automated version of *a segment of the responsibilities I bore as a T3 graphic artist.* To truly propel the progress of audio-tactile graphics authoring tools, there's a pressing need for mechanisms that can automate the extraction and cataloging of such intricate details, storing them in a standardized, accessible format. Such automation not only improve efficiency of the audio-tactile transcription process but can potentially redefine the landscape of tactile graphics creation.

In both Study 2 and 3, the flexibility of the T3 was emphasized by participants, particularly its capability to customize audio-labels based on a student's proficiency in the subject, the immediate task, and the chosen teaching strategy. There was particular appreciation for the T3's feature allowing a single tactile overlay to be repurposed for multiple audio-label configurations. By automating the extraction of semantic information from an image, educators can be liberated from this manual process, enabling them to focus more on crafting layered audio-labels, devising exploration prompts, and conceptualizing various interactive tasks with T3 graphics. This can be achieved using pre-sourced information about both the text and tactile aspects of an image, further streamlining their efforts.

In essence, when discussing automation in the context of T3 utilization in classrooms, the focus should be on aiding educators in crafting T3 graphics tailored to their teaching strategies through extracting and storing *"semantics, syntax and pragmatics"* in a manner that can be easily used to craft a graphic. The goal of automation should be to enhance the educators' role in the process, rather than eliminating their involvement in producing T3 graphics.

The progression towards automation represents a critical advancement in the creation of tactile graphics authoring tools tailored for BVI creators. They inherently understand the subtleties essential for an effective tactile graphics, yet there remains a noticeable lack of tools that enable BVI creators to apply their innate expertise crafting their own graphics. As previously emphasized [61], it is worth noting that many popular tactile graphic production tools (such as Illustrator and Corel Draw) are essentially visual image-editing tools, primarily intended for sighted transcribers. This hints at an implicit assumption in the prevalent tactile graphics production workflow: the need to be sighted to use any tools of production. Filling this gap can lay the foundation for more inclusive, user-driven tactile graphic tools. In her experience designing tactile graphics for herself and several other blind paterons that approach the library for their services, Fleet raises a critical questions about current state of image-access technologies: "What would need to happen to create a straightforward path, navigable by any blind or low-vision person, between feeling curious about a given image and having a tactile version of the image in hand?"[61]

Authoring Tool for BVI creators:

Future research on automation must also delve into the creation of automated tools that grant BVI students the autonomy to produce graphs and charts—a formative learning activity commonly accessible to sighted peers yet challenging for BVI individuals. Innovations like the draftsman[10] and tactile graph paper, as well as Desmos Calculator's sonification of equations [49], represent progress in this domain. Artificial intelligence promises a substantial shift in educational opportunities for BVI students. AI's role extends beyond rendering inaccessible websites and graphics available to BVI users; it also supports authoring tactile graphics, addressing historical obstacles due to technological and practical limitations. Crafting diagrams and figures is vital for sighted students, enhancing comprehension and retention. Autoethnographic accounts from blind university students in an Electrical and Computer Engineering (ECE) curriculum reveal that although tactile graphics are employed for teaching electronic circuit schematics, the absence of comparable reinforcement activities—which benefit their sighted peers in retaining circuit diagram knowledge, such as hands-on lab work and simulation software—impacts their equitable access to a quality education [109]. For BVI students, equivalent educational experiences have been lacking until the emergence of generative AI-based image creation tools, which offer unprecedented avenues for content creation.

Recent advancements in AI-powered authoring tools have introduced methods for assessing the complexity of images [128] and for transforming high-quality images into tactile graphics via machine learning models [77, 177]. However, it is critical to acknowledge that these efforts predominantly aim to automate the role of the sighted transcriber—that is, converting well-prepared graphical images into tactile versions—which represents only a fraction of the comprehensive toolset needed by BVI authors. Typically, these systems require sighted users to select and input high-quality images for processing, which then generates output files that must be managed by a sighted individual for 3D printing or embossing.

While these innovations streamline the transcription process, they do not empower BVI creators to independently produce complex graphics from images. My first study posits that for a truly inclusive approach, it's essential to consider preliminary steps like cleaning and formatting source files as integral to the transcription process, and this perspective also informs my critique of the limited scope of impact of current AI-powered authoring tools.

The transformative potential of AI in this field relies on its thoughtful integration and rigorous testing within authentic educational settings. The mere availability of cutting-edge technology does not suffice; it needs to be interwoven into the learning and teaching milieu of BVI students and their educators with sensitivity and understanding. AI tools should be crafted with a deep awareness of the educational environment, with the intent to complement and enhance established pedagogical goals and practices.

To ensure that the implementation of AI tools is as impactful as it is innovative, they must be aligned with the educational aspirations of BVI students and the teaching strategies of educators. These tools are envisaged to become fundamental to the educational journey, filling current support voids for BVI students. A concerted effort among developers, researchers, educators, and the BVI community is essential to create a suite of tools that cater to the unique educational needs of BVI students and elevate their learning experiences. Generative AI-based assistive technologies should be appreciated not only for their ability to make graphics accessible but also for their potential to enhance classroom participation, facilitate deeper learning, and support long-term academic and professional achievements.

6.4 Socio-Technical Implications of Using the T3 in Classrooms

HCI research on the use of assistive technologies has increasingly emphasized the importance of considering social contexts during the design process [50]. Previous research has shown that people with disabilities often find that assistive technologies lag behind mainstream products in terms of functionality and aesthetics [184]. Additionally, assistive technologies can attract unwanted attention due to their design and potential breakdowns, which can highlight the user's disability [183, 184, 185, 3, 227].

For novel technologies like the T3, which aim to advance the state of the art in image accessibility, it is essential to acknowledge the balance between the utility of audio-tactiles and their social implications. This includes considering the potential for unwanted attention, the impact on inclusion or exclusion from collaborative activities, and the aesthetics of the technology.

Shinohara and Wobbrock, therefore, recommend designing assistive technologies that allow users to express their abilities and identity [185]. For example, research has demonstrated that individuals with disabilities highly value their sense of independence [96] and the outward appearance of being independent [140].

In Studies 2 and 3 with the T3, we gained insights into what independence as an educational outcome meant for teachers and how the T3 facilitated independence for their students. However, it is important to note that our study is limited to the perspectives of the teachers, which does not provide a comprehensive understanding of the social experience of using the T3 as a student.

Future research working directly with students can provide valuable insights into their personal sense of independence and their outward appearance of independence when BVI students use the T3 in classrooms.

Additionally, Shinohara et al. suggest three assistive technology design principles for promoting social inclusion [183]. We believe these principles are crucial for the wider adoption of devices like the T3 in classroom settings. The three principles are as follows:

- Involving users with and without disabilities in the design process to anchor assistive technology design in mainstream contexts.

- Considering both functional and social scenarios of assistive technology use.

- Utilizing design methods that prioritize the social contexts of use.

By adhering to these principles, we can enhance the social accessibility of assistive technologies like the T3 and ensure their effective integration in educational environments.

6.4.1 Limitations of T3

In the context of education, several factors have emerged that limit the use and adoption of the T3, as uncovered across the three studies. Participants in studies 2 and 3 highlighted the **need for additional training, both for themselves and their teams of collaborators**, to be able to consistently create audio-tactile materials. This requirement for training could potentially slow down initial adoption, given the lack of established training plans for educators in this field.

Study 2 illustrated that **T3-based audio-tactile graphics have a longer turnaround time** compared to traditional braille-labeled tactile graphics commonly used by educators. Consequently, the **T3 may be considered a less practical choice for simpler tactile graphics** intended for limited classroom use or non-reusable purposes. Graphics such as those created with Wikki-Sticks or embossers require less time and effort to produce, making them more suitable for such scenarios.

Furthermore, the level of tactile proficiency and familiarity with screen-reader gestures needed to use the T3 suggests that **educators prefer introducing this device to students after they have acquired the necessary prerequisite skills**. In study 3, one participant suggested that the T3 would be most suitable for middle school students.

Lastly, the creation of **descriptive audio labels implies that transcribers and tactile artists must possess a certain level of subject matter expertise** to author these labels effectively. Study 2 participants proposed involving classroom teachers who typically possess this subject matter knowledge in the process of creating audio-tactile graphics. Such an arrangement would further modify the existing workflow for producing tactile graphics.

6.5 Limitations

Despite acknowledging the limitations of individual studies at the end of Chapters 3, 4, and 5, my research also grapples with broader constraints stemming from the general context of the study. All participants hail from the Global North, specifically the United States and Canada. My interactions are concentrated within the states of Michigan and California, owing to my geographical proximity and established connections with educators and organizations serving BVI students. While this afforded me an in-depth view of the local ecosystem, it also narrows the applicability of my findings to the educational frameworks of these regions, as well as to the economic and policy environments that support the availability of VI programs within these states.

The focus of my study primarily involved educators of students with visual impairments, rather than the students themselves. This was a deliberate decision during the design phase of the study. Consequently, the insights into the efficacy of my designs are indirectly conveyed through the educators' feedback and their observations of the students' academic and classroom achievements. This approach, while informative, precluded the opportunity to collect firsthand input from the students, which would have provided invaluable and compelling perspectives to juxtapose with the experiences of the educators.

Furthermore, the third study entails a deployment investigation that examines the relatively long-term use of the device. However, to gain a comprehensive understanding of the instructional success of devices like the T3, and to assess the academic advancement of students utilizing it, it is crucial not only to gather insights over extended periods but also to accumulate quantitative evidence of the students' improvement. This endeavor would necessitate the development of robust authoring software for T3 graphics and a comprehensive training program for educators. Although this presents a complex challenge, it undeniably points to a pivotal area for future research to address these identified gaps.

6.6 Summary of the Chapter

While prior literature acknowledges the numerous advantages of audio-tactile graphics for BVI readers in deciphering complex tactile graphics, there remains a scarcity of practical knowledge regarding the successful support and implementation of such systems within real-world settings, such as educational institutions. This dissertation presents three studies that seek to bridge the current understanding gap concerning the overall utility of audio-tactile graphics within educational contexts.

In the first study, we engaged transcription professionals from schools and transcription agencies to delve into their workflows, collaborative efforts, and workplace factors influencing their design processes. Although both contexts employed the same toolset, the workflows and design decision-making processes varied considerably. This suggests that contextual factors critically influence the utilization of authoring tools for producing tactile graphics.

The second study homes in on transcription within the school environment. Practitioners engaged in designing and teaching with tactile graphics were invited to participate in a co-design workshop. Here, we observed their collaboration, utilization of available tools, and the creation of an audio-tactile graphic for the T3 tablet based on a given prompt. Subsequent focus group discussions revealed that while the ad-hoc design workflow for T3 graphics was feasible within their current workplace context, it significantly altered the practitioners' traditional job roles. The discussions also highlighted how audio labels could be structured to bolster tactile exploration and enhance independence among novice students. However, the time investment needed to produce detailed audio-tactile graphics might not be practical in all scenarios. This raises a pivotal question: Under what circumstances would educators prefer the T3 graphics over other available methods for presenting information, such as various tactile graphics forms and verbal descriptions?

The final study introduced the T3 tablet into classroom settings, alongside other assistive technologies, over a six-week period. The objective was to determine whether audio-tactile graphics designs could help educators achieve their pedagogical goals through both traditional and innovative teaching methods and if our provisional design workflow was compatible with existing workflows for creating tactile graphics. The T3 was found to be compatible with the teaching methodologies of participating TVIs and supported several predefined educational goals, notably enhancing autonomy among novice tactile graphics readers. This study underscored the need for robust authoring tools for audio-tactile graphics and a comprehensive training plan for educators to design their own graphics, paving the way for sustainable technology deployment. Although the audio-tactile workflow altered educators' roles, it also prompted discussions on the positive changes that could involve classroom teachers more directly in creating accessible educational content for BVI students. Yet, this remains a topic for future inquiry.

In this chapter, we extrapolate the insights from these studies to chart future research directions for image-access technologies. We consider how the presence of other assistive technologies might influence the expected outcomes of new technologies and the design considerations required for assessing their practical utility. We revisit the UDL-infused TPACK framework to dissect our findings and propose next steps for the successful classroom integration of T3-like devices from an educational technology research standpoint. The PEO (Person-Environment-Occupation) model of assistive technology is referenced to discuss the multifaceted technology network that constitutes the 'environmental' factors affecting novel technology design and deployment. Additionally, I discuss considerations for research into the automation of the transcription process, its potential to empower BVI individuals to author their own graphics, and the applicability of insights from my research to such endeavors. The chapter concludes by acknowledging limitations that constrain the reach of my research and its applicability beyond the North American educational system context.

CHAPTER 7

Conclusion

This dissertation presents a structured evaluation of the use of audio-tactile graphics—a recent and lauded adaptation of traditional tactile graphics—in educational settings. To achieve this, it was imperative to comprehend the operational context, the end-users, and the specific workflow involved. The first study illuminates the various scenarios in which audio-tactile graphics might be crafted and applied. The subsequent stage was to examine the production process of these graphics. This was explored in the second study through co-design workshops, which aimed to capture the methods by which transcription teams would approach the creation of audio-tactile graphics. After modeling the production process, the next phase involved evaluating whether these graphics satisfied educational objectives and supported educators' teaching methodologies while being congruent with established practices. This was put to the test by integrating the T3 into two classrooms, each involving a teacher of the visually impaired (TVI) and a student, over a six-week period. Together, these studies offer valuable insights for the broader adoption and sustained use of audio-tactile graphics.

The efficacy of assistive technologies for BVI users does not only hinge on their usability and effectiveness but also on the broader ecosystem within which they are used to achieve specific tasks or outcomes. In educational contexts, this ecosystem is supported by educators' workflows that ensure classroom materials and course content are accessible through tactile and audio alternatives, enabling BVI students to participate alongside their sighted peers. My dissertation explores how we can support the sustained use of audio-augmented tactile graphics by leveraging and adapting these existing ecosystems to facilitate the design and instruction using audio-tactile graphics.

Throughout my dissertation, I have implemented an ad-hoc workflow that complements and can be integrated into schools' existing workflows, using tools typically employed for producing traditional tactile graphics. In scrutinizing this workflow, I have identified the need for educator training and the development of advanced authoring tools as essential for the prolonged use of audio-tactile graphics.

Educators' adoption of audio-tactile graphics depends on their effectiveness in achieving the specific educational outcomes set for their students. My thesis has confirmed these potential advantages of audio-tactile graphics in classroom and O&M settings. During a six-week deployment, we discerned areas where audio-tactile graphics surpassed traditional tactile graphics, like fostering autonomy in graphic exploration, and areas where they did not perform as well, such as in navigation exercises.

By contextualizing audio-tactile graphics within the educational environment, I perceive them not merely as a tool for accessibility but as an impetus for a transformative educational experience for BVI students. This includes innovative teaching methods that engage students with interactive audio-tactile graphics, the production of detailed tactile graphics with comprehensive audio descriptions, and the encouragement of cooperative activities between sighted and blind students using audio-tactile interfaces. These insights provide a basis for future research directed at facilitating the broader adoption of audio-tactile graphics.

This work contributes to the foundational knowledge of Technological Pedagogical Content Knowledge (TPACK) for audio-tactile interfaces by detailing the technological processes involved in creating and interacting with audio-tactile graphics in educational settings, advocating for ways to incorporate of these graphics in both current and emerging pedagogical strategies, and outlining design guidelines for the conversion of visual graphics into audio-tactile formats. At the heart of this research is the goal to uncover methods that facilitate the migration of audio-tactile graphics from the realm of research into actual classroom use. Through my studies, I have provided insights into the broader design considerations necessary for integrating audio-tactile graphics within educational systems.

APPENDIX A

Study Protocols

A.1 Study 1 Interview Protocol

- To begin with, can you talk a bit about yourself?
  - How long have you been working as a transcriber/proofreader?
  - What type of material do you transcribe/proofread?
  - The organization you work with?
  - Type of clients you work with?
- Proof Readers Do you work with a copyholder? Who do you work with? Are there any sighted proofreaders?
  - For what tasks do you involve other people in your process? How do you collaborate with them?
  - Why?
  - Do you work with transcribers?
  - If Yes, how does it it happen?
  - If not, How would you imagine the collaboration with transcribers/proofreaders would be, in terms of the flow.
- Transcribers Do you work with proof readers? At what point in the transcription process do you typically interact with the proofreaders?
  - What works well in such a collaboration
  - What would you want to do differently?
- Where do you typically work?

- Can you walk me through the steps you take in transcribing/proofreading?
  - So if you can sort of think about what kind of thought process happens when you decide what needs to be drawn and what needs to stay?
  - How do you decide what needs to be added to the drawings and what should go?
  - Probe questions depending on the descriptions.
- Can you recall an instance where you've had to verify whether a picture is able to convey the meaning well, does it serve the purpose in a textbook/pamphlet/exam etc?
  - What factors do you typically consider when evaluating
  - Probe questions depending on the descriptions
- Are there any guidelines that you typically follow when proofreading the graphics?
  - Do you have your own guidelines?
  - Can you recall the last diagram that you had proofread?
  - How did you communicate your feedback to the designers/transcribers?
  - Can you recall the last time you had to think outside of these guidelines?
- Can you recall the last time you have had to verify the effectiveness of a transcribed graphic? What are the factors that you look out for when proofreading these graphic?
  - What are the factors that affect the graphic designs?
  - What kind of feedback do you typically provide for transcribed graphic?
  - Can you recall an instance when you found including more or excluding some of the standard information from the print copy has resulted in an effective graphic design?
- How much does a reader's skills, knowledge, experience, or expertise factor in the way you assess the tactile graphic?
- In terms of complexities, can you recall an example of a tactile graphic that was most complex or loaded with information that you had to transcribe/proofread?
  - What was the purpose of this graphic?
- If you had to make a change to one of the steps involved in this large effort with multiple stakeholders for producing tactile graphic for students, what would you do differently or would like to improve?

A.1.1 Demographic Questions

- Which of the following brackets does your age fall under:
  - 18-23
  - 24-30
  - 31-40
  - 41-50
  - 51-65
  - 65 and above
- What gender do you identify as?

A.2 Study 2 Interview Protocol

A.2.1 Part 1: Introduction to T3

Hi all, thanks for participating in this co-design study today. My name is Hrishi and I am going to be the facilitator during this session. Through this study, we are looking to design tactile overlays for a touch-input tablet: T3. This device is used for producing audio supported tactile graphics as I will show you with a few examples. The current process of producing these graphics requires a specific type of equipment for printing the tactiles, and a designer who also programs them to embed audio announcements for each unique tactile overlay. We are trying to assess if this device can be used in a classroom setting by a TVI for supporting visually impaired students. We are trying to learn whether How do the audio tactile graphics produced during this workshop compare to tactile graphic when it comes to communicating visual information? Is it easy to produce tactile overlays and program the audio announcements on the T3? And Is this process of producing audio-tactile graphics compatible with the existing processes that TVIs follow when producing tactile graphics in a timely manner, using a visual source of graphics.

The workshop today is divided in to three parts: In the first part: I will show you some demos on T3 using a few overlays that the manufacturing company named Touchgraphics, has provided. I will explain how it works and how can you load any examples from this demo. Feel free to interact and play around with the T3 during this session.

In the second part: We will all work together to produce a tactile overlay that goes on top of the T3. I will provide you with a prompt and a visual graphic. I would like for us to create a tactile overlay version of this graphic and I will work with you to program the T3 to announce the labels you choose to have announced and any information that you would like to layer. During this session, I will be asking you questions about your design decisions. It may seem like a very obvious question, but I just want you to explain in your own words so I don't walk away with assumptions based on my observations.

In the third part: We will do the same task as in the second part, except this time, you can choose the prompt of your choice from something you recently worked on. If you have brought a digital copy of the image, that would be great as it will help us design the image quicker. I will be assisting you with any image editing you may need during this session.

And Finally, we will conclude this workshop by doing a debrief session during which I would like you to imagine teaching your students how to read the tactile overlay using the T3. How do you imagine the process of producing audio-tactile graphics changing the way you currently organize your workflow for producing tactile graphics? Could you develop these designs using the tools you currently have access to at school? Would you say this communicates the same level of information as the traditional tactile graphic? Any other types of graphics that you can think of that you would like to use on the T3?

I would like ya'll to remember to think out loud as you perform these tasks. I want to learn what are some of the things you all consider when deciding how you design a graphic. There are no right or wrong answers here, and I will be learning from you.

Do you have any questions for me at this moment?

A.2.2 Part 2: Design Activity with Hurricane Ian Prompt

Prompts that I used to encourage participants when they were working on the design activity

A.2.2.1 Before starting design

- What information from this visual diagram would you choose to retain and what information would they like to leave out of the tactile diagram?
- Is there anything that you would like to discuss with the student or the classroom teacher or the para educator at this point, before you begin your design?

A.2.2.2 During Design

- Compared to a regular tactile diagram, how would you describe our design to be different?

if it has a key How would you add the key to the figure?

- Does it concern you that listening to audio-labels instead of reading braille can negatively affect their exposure to braille?

- Does that factor into what information you choose to include as braille vs audio announcements?

A.2.2.3 Post Design:

- Among your current and former students ,can you imagine someone that could benefit from having this audio-tactile version of the graphic instead of a tactile-only version?

- How do you imagine teaching your students using this audio-tactile graphic on the T3?

- If you student requests to change something or make minor edits, how do you imagine that process would look like when using the audio-tactile graphic instead of just tactile? [Assume that you had all the required experience to produce these on your own]

A.2.3 Part 3: Focus Group Questions

- Now that we know how audio-tactiles are produced, Can anyone comment on whether your students would find the audio-tactile graphics produced on T3 useful?
  - How does it fit it into your current process
    - For producing tactile graphics.
    - For teaching students using the resulting graphics.
  - Can you comment on one thing that audio-tactile graphics allow you to do that tactiles don't?
  - Can you imagine a scenario where your students are involved in creating some of the content themselves?

Open- ended questions about their experience designing the graphics and how they would imagine creating these graphics in a classroom. Examples of such questions include:

- How much training do you imagine your students would need to be able to use this device?

- Discuss: considering how teachers and para educators currently teach using tactile diagrams in a classroom, what changes in the instruction/classroom organization do you foresee if students were to use audio-tactile diagrams?

- Can you imagine using this in your day-to-day workflow to create tactile overlays and program them on T3?
- What kind of support (technology wise and also training wise) do you think you would need if you were to try and use it in your classrooms and with your students?
- Do you see any limitations with T3 currently that make you feel tactile graphics would serve better?
- What type of images would you like to see in audio-tactile form?

A.3 Study 3 Background Interview Protocols

- Without revealing identifiable details such as their exact grade, name, or gender, can you provide some information about the student who you are considering using the T3 with?
  - Subjects they use tactile graphics for?
  - High-school / Middle school?

A.3.1 Student Specific Questions

- Can you discuss your students' experiences using tactile graphics?
  - Have they used tactile graphics before?
    * If so, what types of tactile graphics have they used and how often?
  - Have they expressed any preferences or difficulties when using tactile graphics?
- On average, how many times per week do your students work with tactile graphics specifically (not including braille text or other materials)?
  - Can they use them independently?
  - Would you say they like reading tactile graphics?
- What other accessibility technology does the student use?
  - Where do they have access to this technology? (classroom, home, etc.)
  - How long have they been using it?
- Why do you think this student should try using the T3? Can you discuss their:

  - Tactile graphic skills
  - Braille reading skills
  - Most recent tactile graphic that they found challenging to read/use
    * What was the reason for the difficulty?
    * What teaching strategies were used?

- Could you describe the last tactile graphic that you taught your student?
  - What was the purpose of the graphic?
  - What tasks did the student perform with the graphic? Homework, classroom discussion, assessment, explaining a concept, etc.?
  - Was the design intended to be used by the student independently or with a para-teacher?
  - How did you pre-teach the graphic? What did you cover?
  - How long was the pre-teaching session?
  - Do you typically spend a similar amount of time pre-teaching?
  - Did you meet with the student again after pre-teaching?
  - Did you receive any feedback from the student or make any just-in-time edits during these sessions?

- What other tactile graphics are you planning to create for your students based on their curriculum this year?
  - What is the subject?
  - How long will the students use these graphics?
  - Can you explain how a student would use this tactile graphic in the classroom?
    * Would they use it for independent learning or with assistance?
    * What tasks would it support?
  - Typically, how much time would you spend pre-teaching this graphic?
    * Can you walk me through what you would cover when pre-teaching?
    * When do you know a student has learned what was pre-taught and is ready for the class? How long does it typically take?
    * How long would you discuss this tactile graphic in class?
  - Can you think of any particular types of graphics from your students' curriculum that you would like to see on T3? Why?

A.3.2 Teacher Specific Questions

- How many students do you work with currently?
- On average, how much time do you spend working on materials for each student?
- What is the most time-consuming aspect of your job?
- Do you create any tactile graphics, drawings, or modify existing graphics when working with your students?
  - If yes, when do you create them, what tools do you use, how often do you create them, and how long does it take to make these changes to tactile graphics?
- Do you involve your students in the tactile graphics design or modification process? If so, how?
- What educational outcomes do you hope to achieve by using T3?
  - How would you typically measure such an outcome if you were using a tactile graphic?
- Can you describe your collaborations with other educators, such as para-teachers or tactile artists, when creating tactiles for your students?
  - How do you imagine these collaborations playing out with T3?
  - On average, how much time do students spend with a para-educator?

A.3.3 Study 3 Diary Response Questions

The questions were on a form that teachers filled out after sessions with students using the T3 device. Filling out the form took no more than 5 minutes. The diary entries gave us a brief look at how teachers and students interacted, which we talked about more in our weekly interviews.

The diary prompt consisted of the following open-ended questions:

- What did you go over with your student today?
- What stood out in your experience of teaching using the T3?
- How did your students find working with the T3 today?
- Why did you choose to use the T3 for this over other materials?
- What would you like to improve about your experience of teaching with the T3 today?

A.4 Study 3: Weekly check-in Protocol

Opening Questions

- Can you walk me through how you taught this graphic (using the T3) to your student this week?
  - What was the objective of this graphic?
  - Any strategy used to teach?
  - Any other comments?
  - Who all worked with her?

Graphics Related Question [changed every week]

- For what type of exercise di your student used this tactile graphic?
  - Any independent exploring?
  - What questions did they have when they first read the graphic?
  - Would they be using these images at home/classroom/independent time?

Graphic Specific Questions [Changed Every Week]

- (P1 WEEK 1) Can you comment on your students preference regarding braille versus audio input for key
- (P1 WEEK 1) How long did it take for them to learning time to get used to T3

Factors for Long-Term Adoption of T3

- Can you comment on the following aspects of using the T3 to teach [Questions derived from previous research]:
  - The time you spent teaching the tactile graphic using T3 as compared to if it had been a tactile graphic?
  - Would you say the student was interested in using the T3 to access tactile graphics?
  - Your student's ability to independently read Tactile Graphics on T3 as compared to without it?

- If used in classroom setting: Was the student able to follow along with the teacher in the classroom when using the T3?
  * If used in a different setting: Did the student meet the expected pace of reading the tactile graphic?
- At any point did you think that this graphic on the T3 could be potentially reused or repurposed for a different lesson?

APPENDIX B

Study 2 Co-Design Workshop Prompt

B.1 Hurricane Ian

Next week, freshmen students at pioneer high school will be learning about hurricane Ian as part of their geography class. You are creating a tactile diagram for James, a student with congenital blindness. James has 5 years of experience using tactile diagrams in school. Design an audio-tactile image to explain how hurricane Ian travelled across the Southeastern US states in Sept 2022. The following prompt highlights details that the classroom teacher wishes to cover when discussing the timeline of hurricane Ian.

B.1.1 Origin:

Around mid-September: Ian originated as a tropical wave in tropical Atlantic waters off western Africa. Ian continued to move towards the cooler northern Atlantic waters near the North American shores, passing through the Caribbeans. September 24: Ian strengthened up to a category three hurricane near Jamaica. Within the next 72 hours, Ian caused widespread damage and flooding as it passed over Cuba, Jamaica, and the Cayman Islands.

B.2 Ian in the US:

B.2.1 Morning of Sept 28, Category 4:

Ian continued moving northeast, towards the west coast of Florida. Before it had even made landfall, Ian had already left half a million residents in Fort Myers and North Naples without power and several hundred thousand homes were flooded.

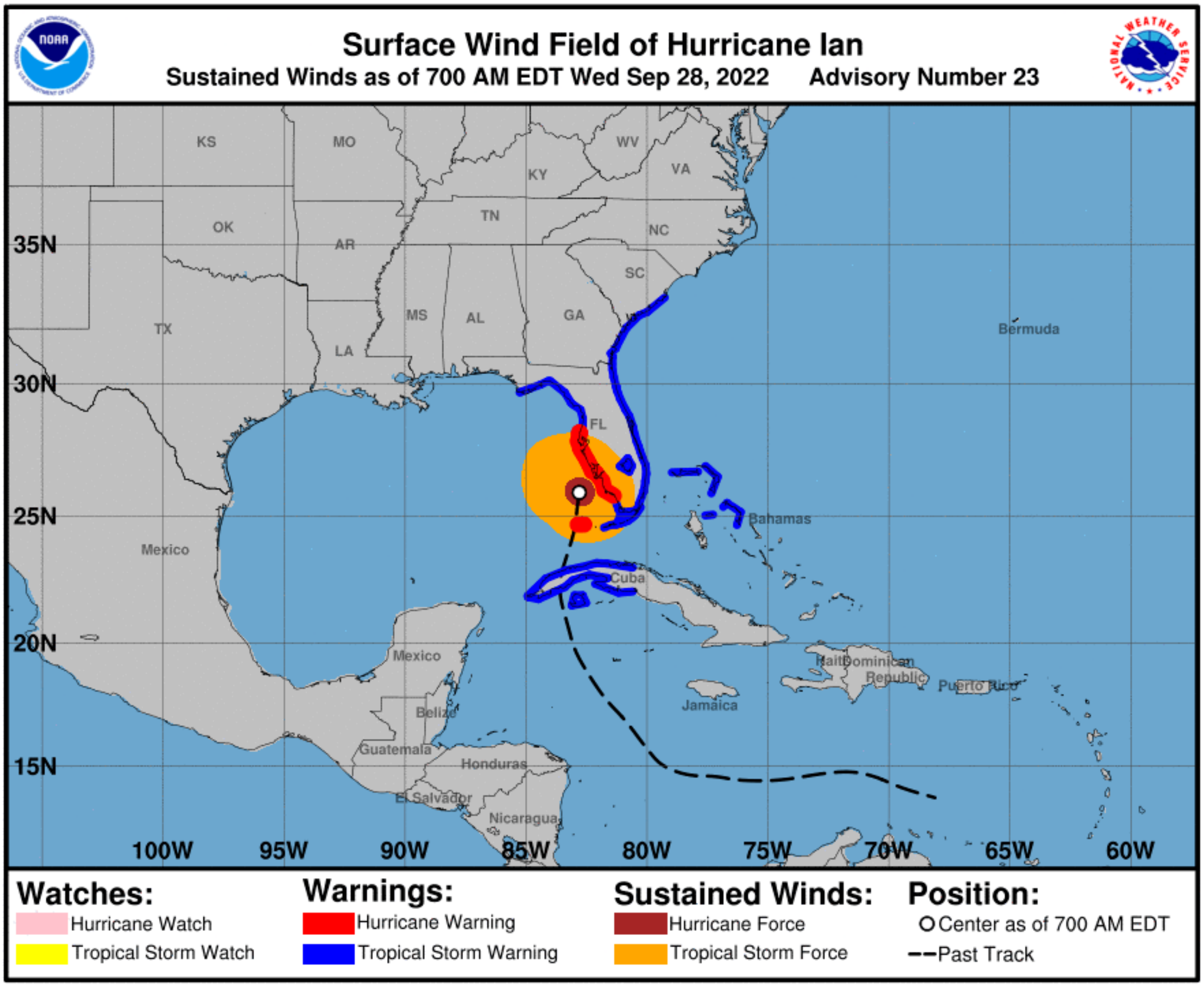

Figure B.1: Morning of Sept 28, Category 4

B.2.2 Afternoon of September 28, Category 4:

Ian, still in Gulf of Mexico, continued to absorb moisture and reached its highest recorded speed of 155 mph. By 2PM, Ian made landfall directly over Cape Coral Islands near Fort Myers, and then made its way inland, still registering as a category four hurricane. By now more than 90% of Fort Myers residents were without power.

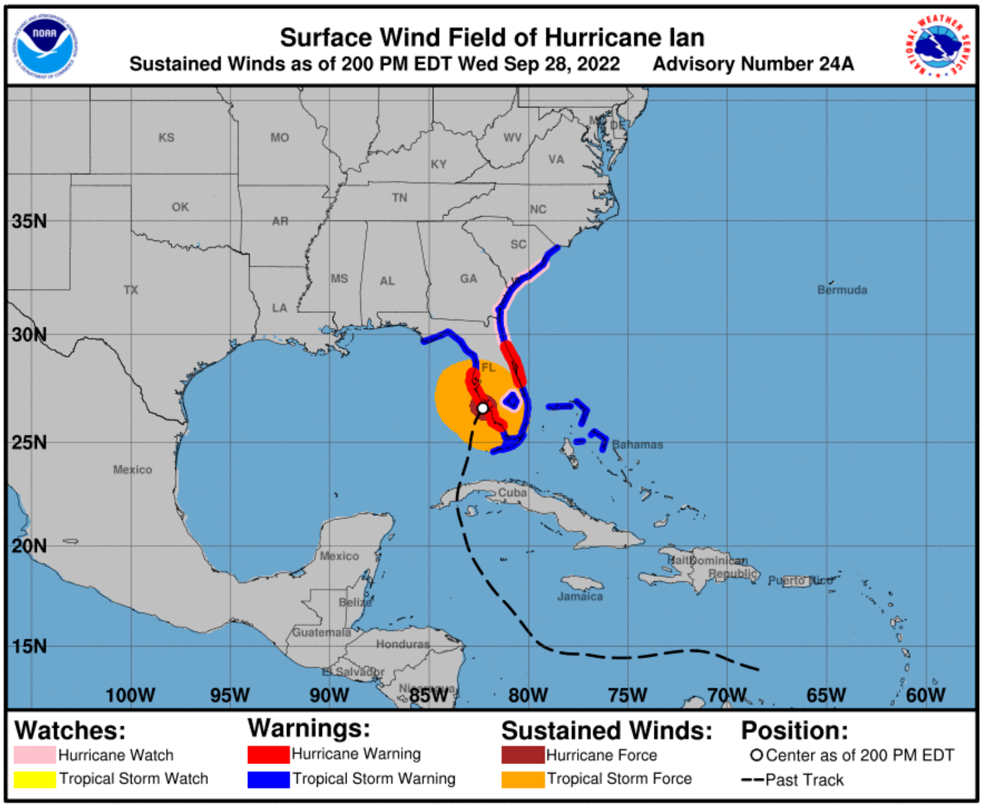

Figure B.2: Afternoon of Sept 28, Category 4

B.2.3 Midnight of Sept 28, Category 1:

Ian continued to make its way across central Florida. However, as it moved over land, it lost its speed and strength. Ian slowed down to a Category 1 hurricane by the time it crossed

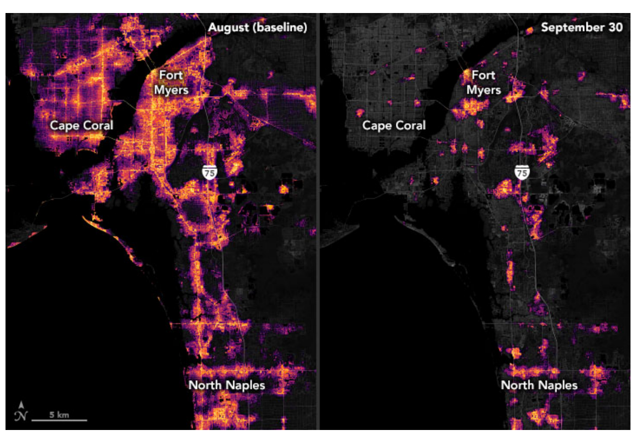

Figure B.3: Satellite Image of Fort Meyers Area in August and On Sept 30 showing the loss of power in areas affected by Hurricane Ian

Central Florida 70 miles south of Orlando.

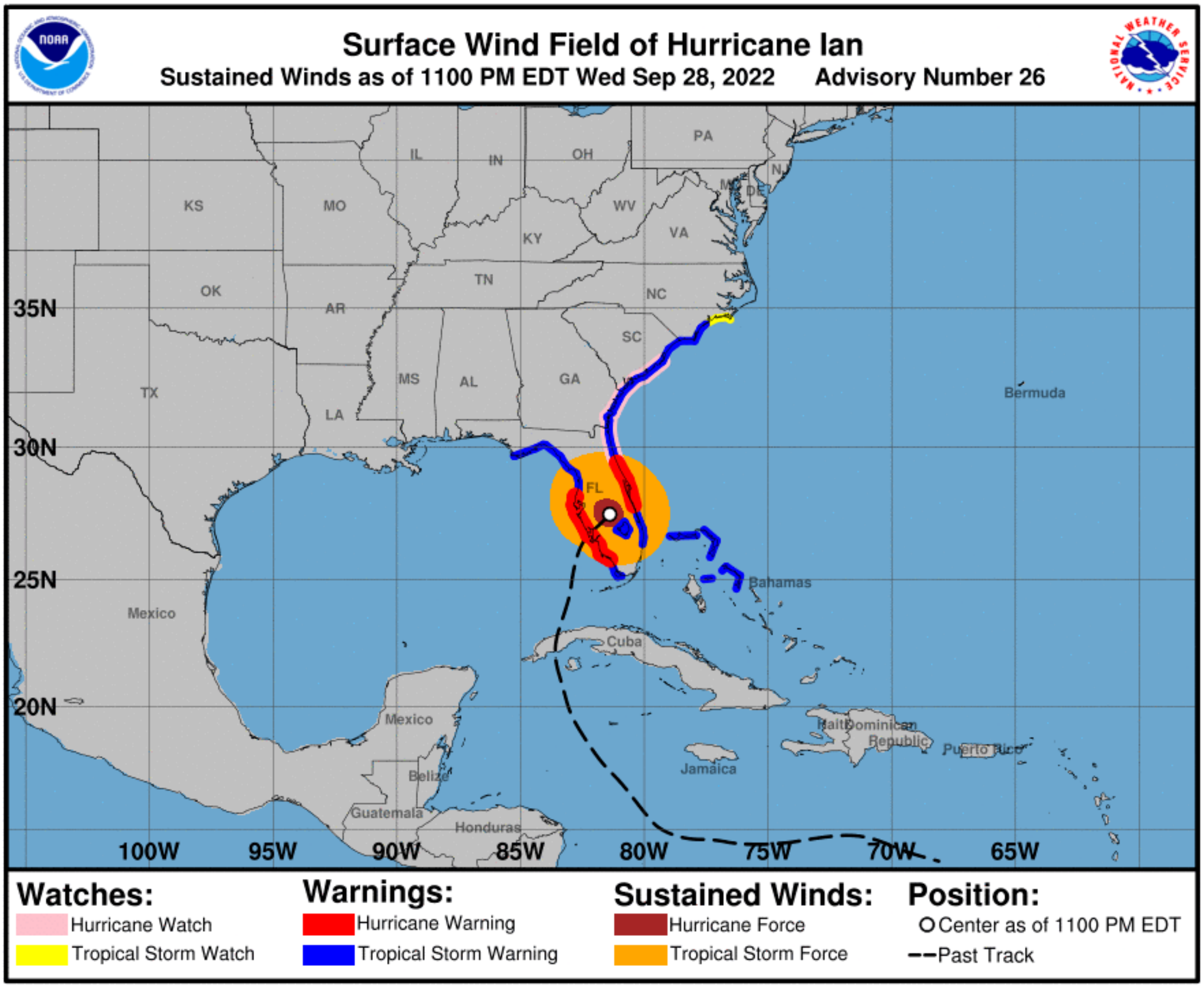

Figure B.4: Midnight of Sept 28, Category 1

B.2.4 Morning of Sept 29, Tropical Storm:

Ian reached Cape Canaveral on the east coast of Florida. While it had slowed down to a tropical storm, its effects could still be felt from hundreds of miles away, across Florida, Georgia, and South Carolina. Ian continued to move north-east, making its way over the Atlantic Ocean, and would travel along the coast of Georgia.

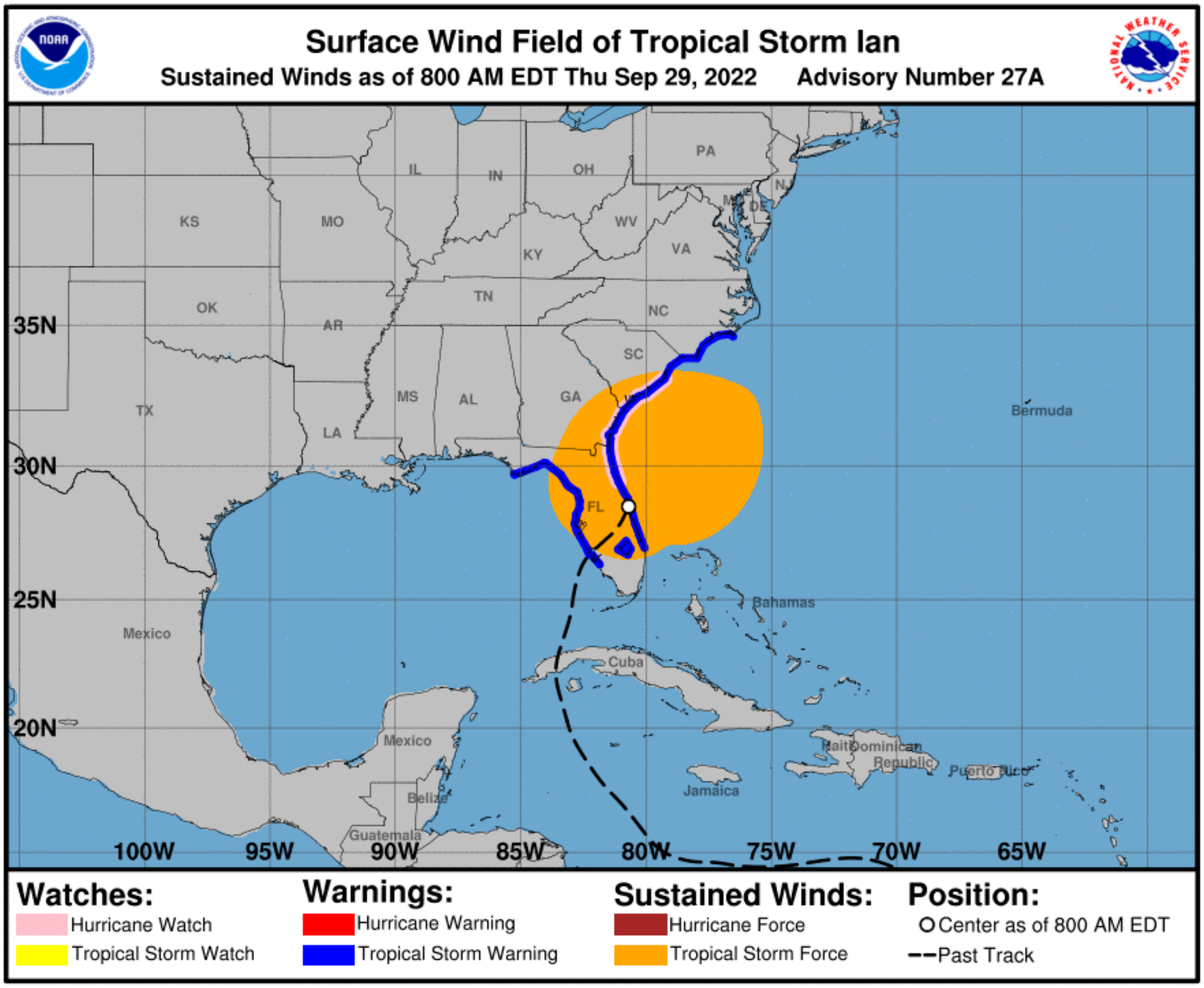

Figure B.5: Morning of Sept 29, Tropical Storm

B.2.5 Morning of Sept 30, Category 1:

As Ian travelled over the Atlantic ocean, it absorbed moisture and winds and strengthened up to a category 1 storm as it made its way towards South Carolina. Ian was less than a hundred miles away from the coast and appeared to be headed towards Myrtle Beach, SC.

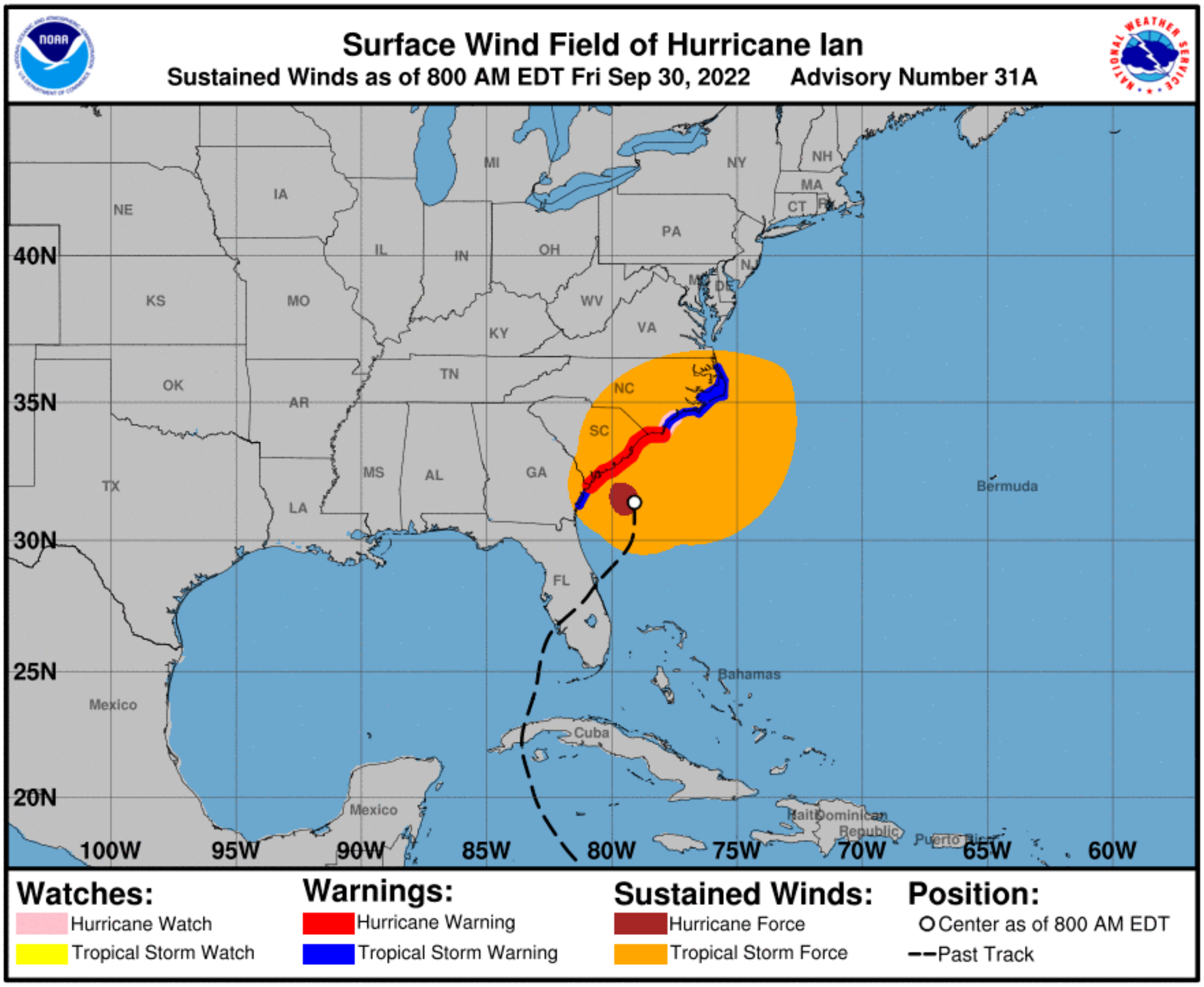

Figure B.6: Morning of Sept 30, Category 1

B.2.6 Afternoon Sept 30, Category 1:

Ian made a direct landfall over Myrtle Beach as a Category 1 hurricane. As it continued to make its way inland, Ian started losing its strength again and is reclassified as a tropical storm. At this point Ian appeared to be headed further north and toward the South Carolina - North Carolina border.

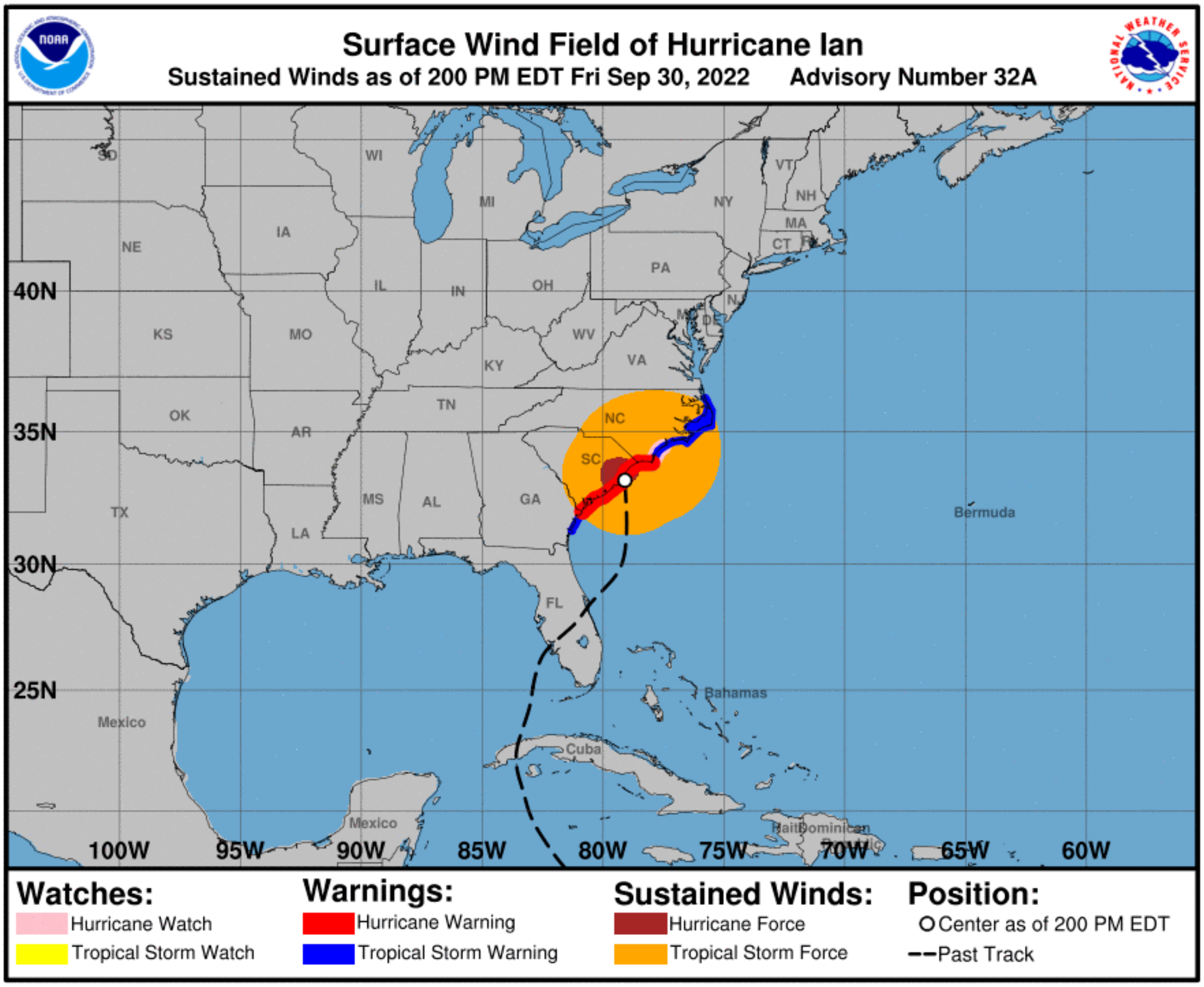

Figure B.7: Morning of Sept 30, Category 1

B.2.7 Evening of Sept 30, Post tropical cyclone:

Ian was about 60 miles south of Greensboro, NC when it changed its direction again to move eastward along the NC - Virginia border. It continued to slow down further and by the next morning (Morning of October 1), Ian disappeared into a local thunderstorm before the shores of NC.

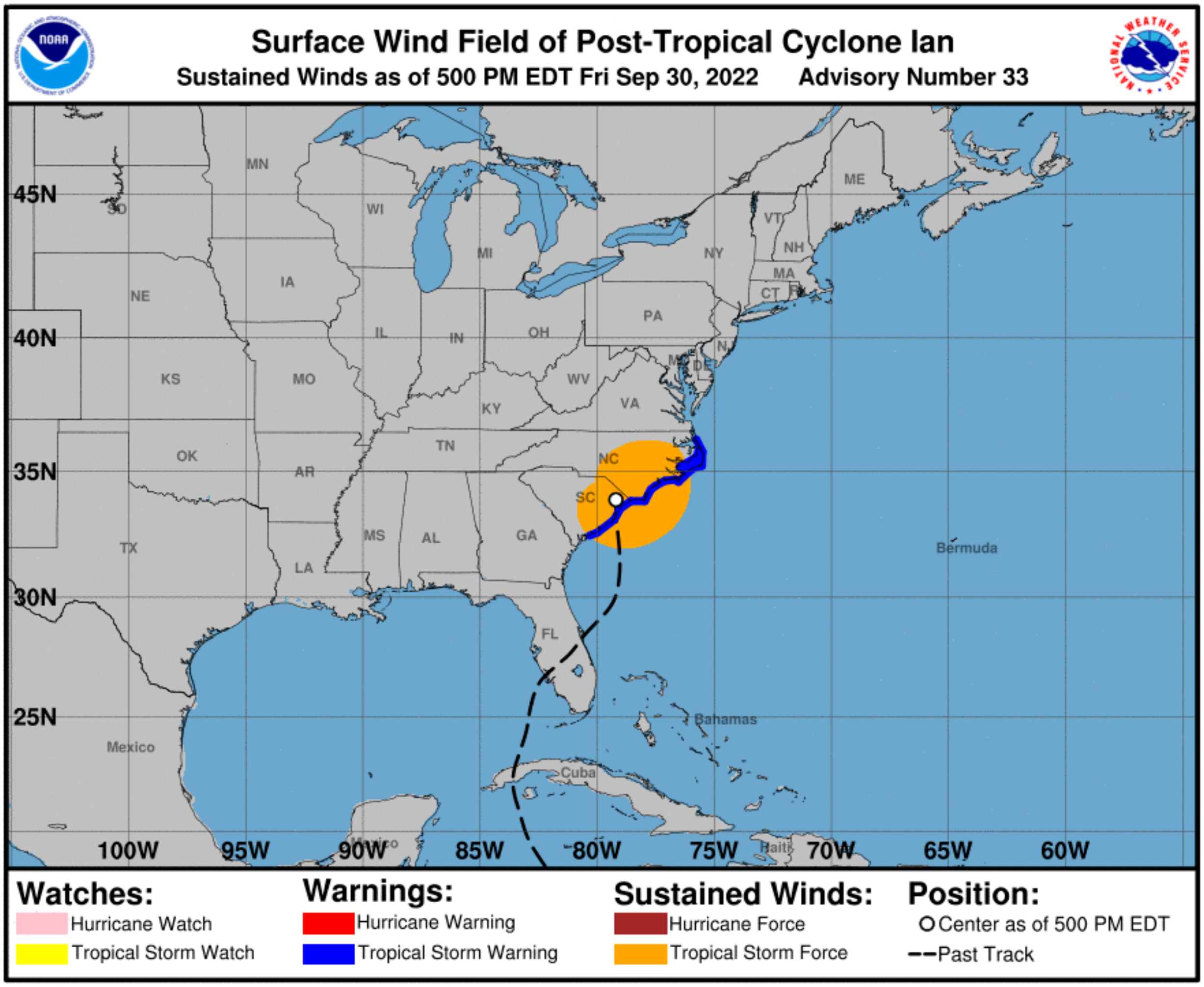

Figure B.8: Evening of Sept 30, Post tropical cyclone

B.2.8 Overview of the Path Followed

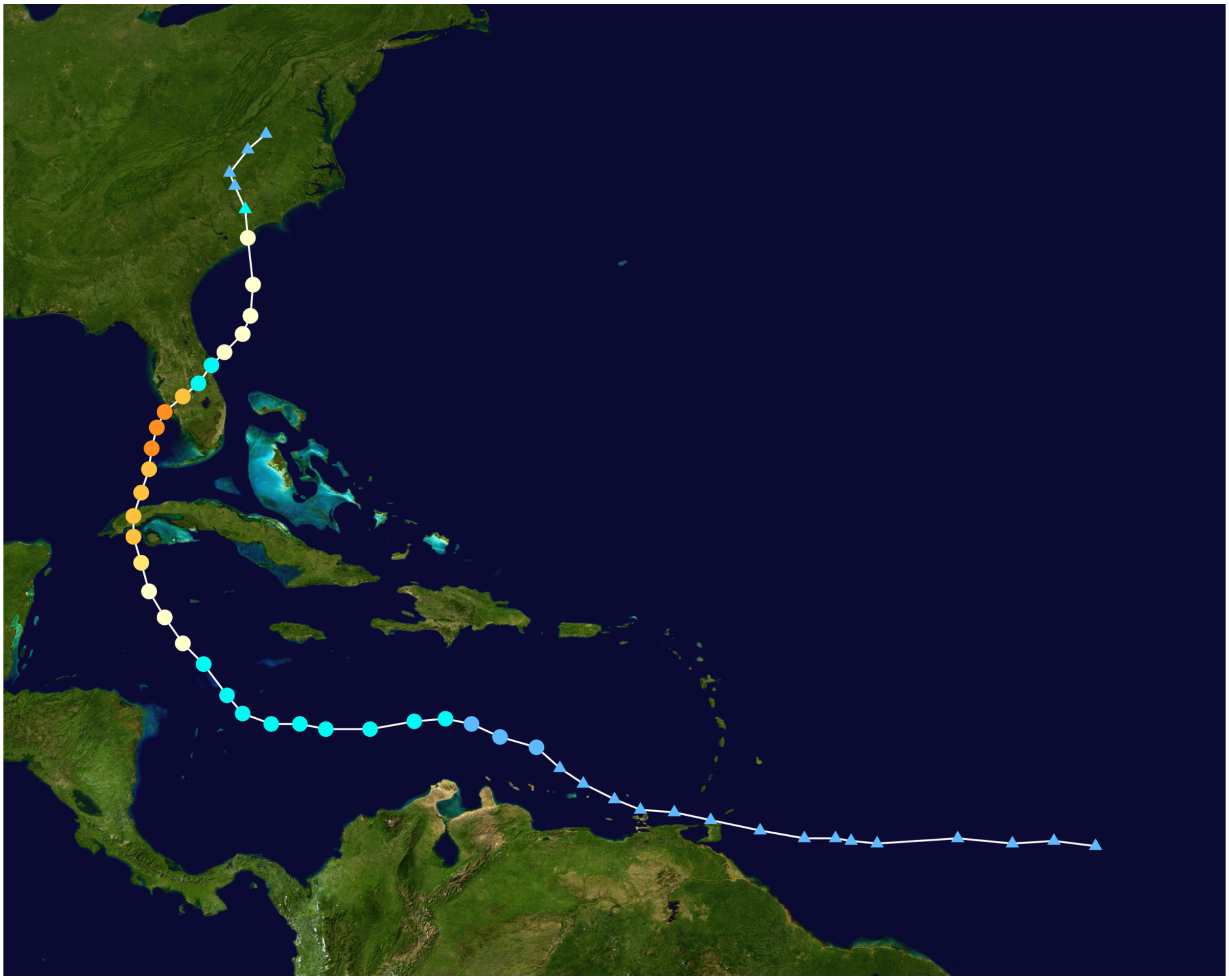

Figure B.9: Path map of Huriicane Ian (2022). Source: Wikipedia

APPENDIX C

T3 Graphics Created During Studies 2 and 3

C.1 Co-design graphics

C.1.1 T3 Hurricane Path Map Created in Workshop #1

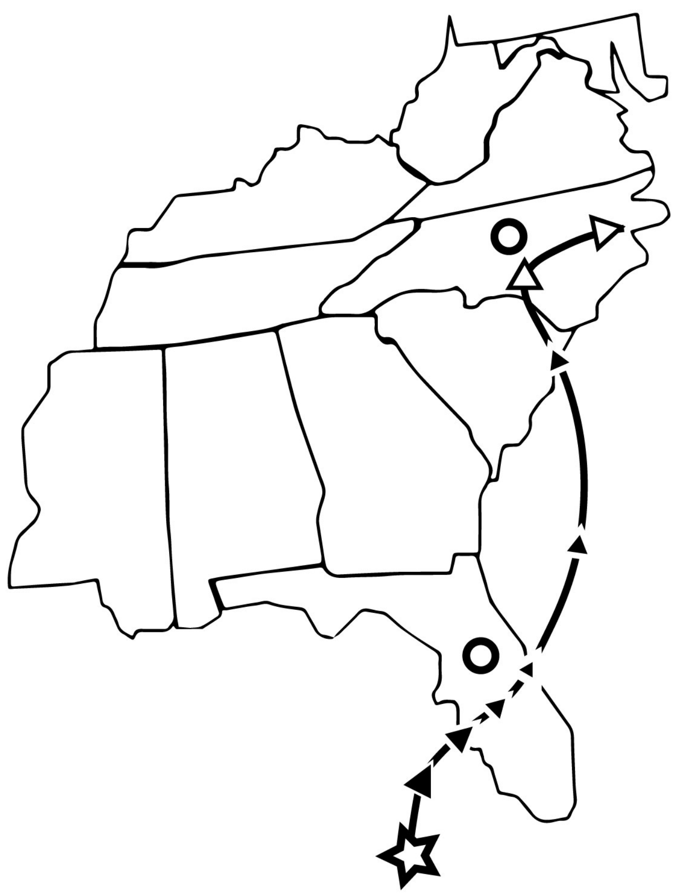

Figure C.1: Hurricane Path Map from Co-Design Workshop #1

C.1.2 T3 Hurricane Path Map Created in Workshop #2

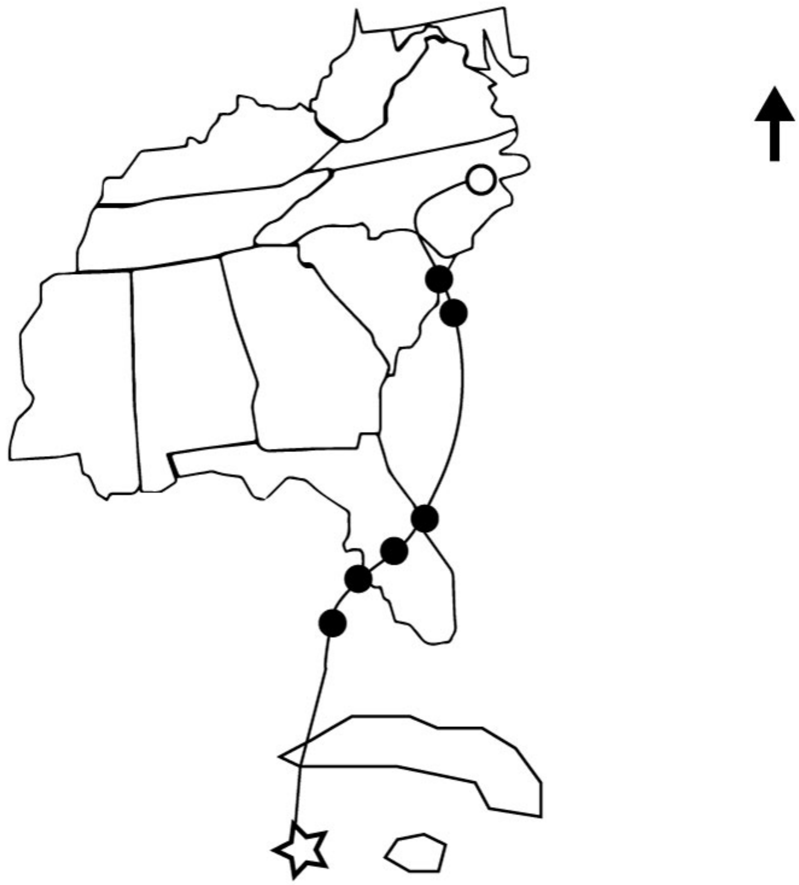

Figure C.2: Hurricane Path Map from Co-Design Workshop #2

C.2 Field deployment graphics

C.2.1 Graphics For P1 and S1

C.2.2 T3 Graphics Used By P2 and S2

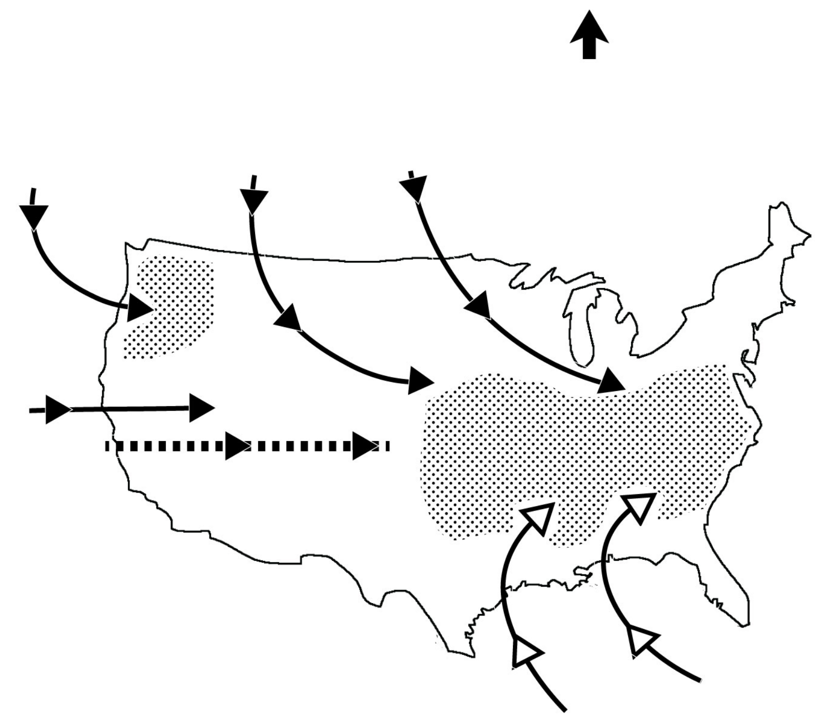

Figure C.3: Week 1 Graphics

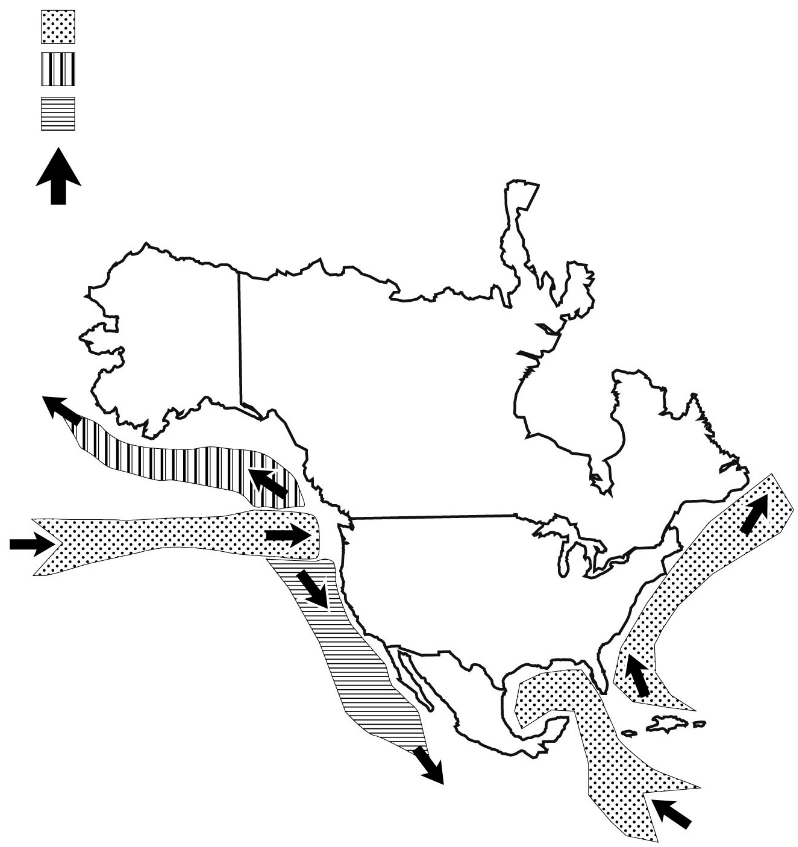

Figure C.4: Week 1 Graphics

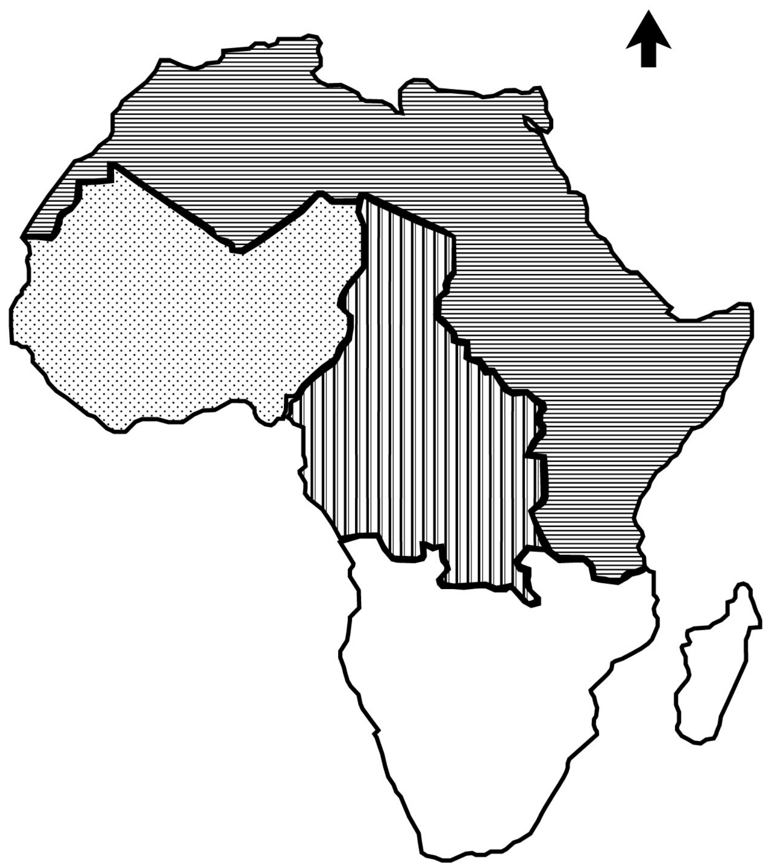

Figure C.5: Week 2 Graphics

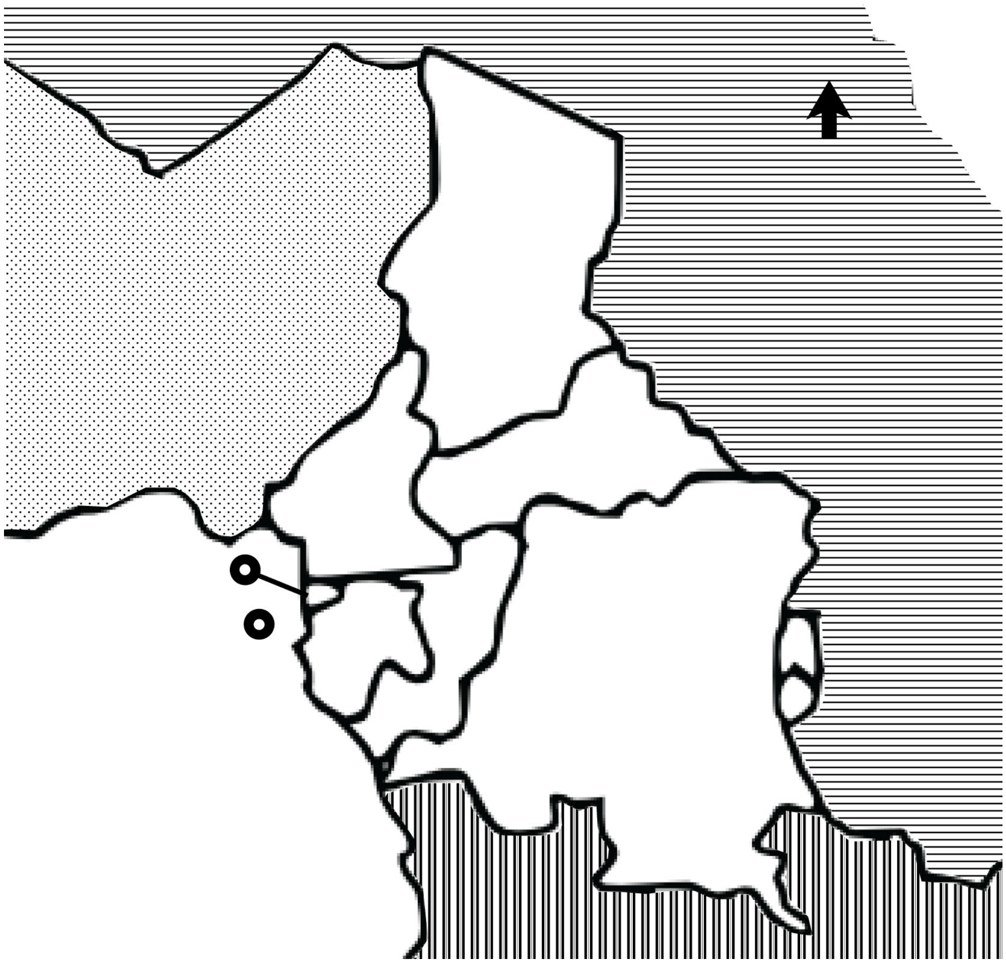

Figure C.6: Week 2 Graphics

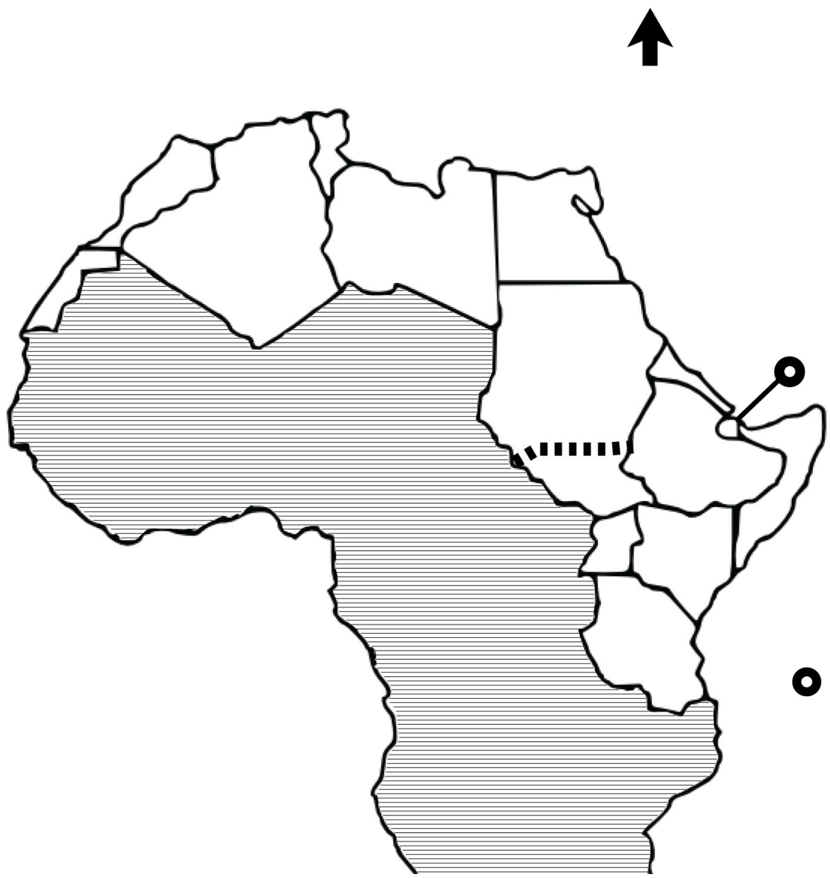

Figure C.7: Week 2 Graphics

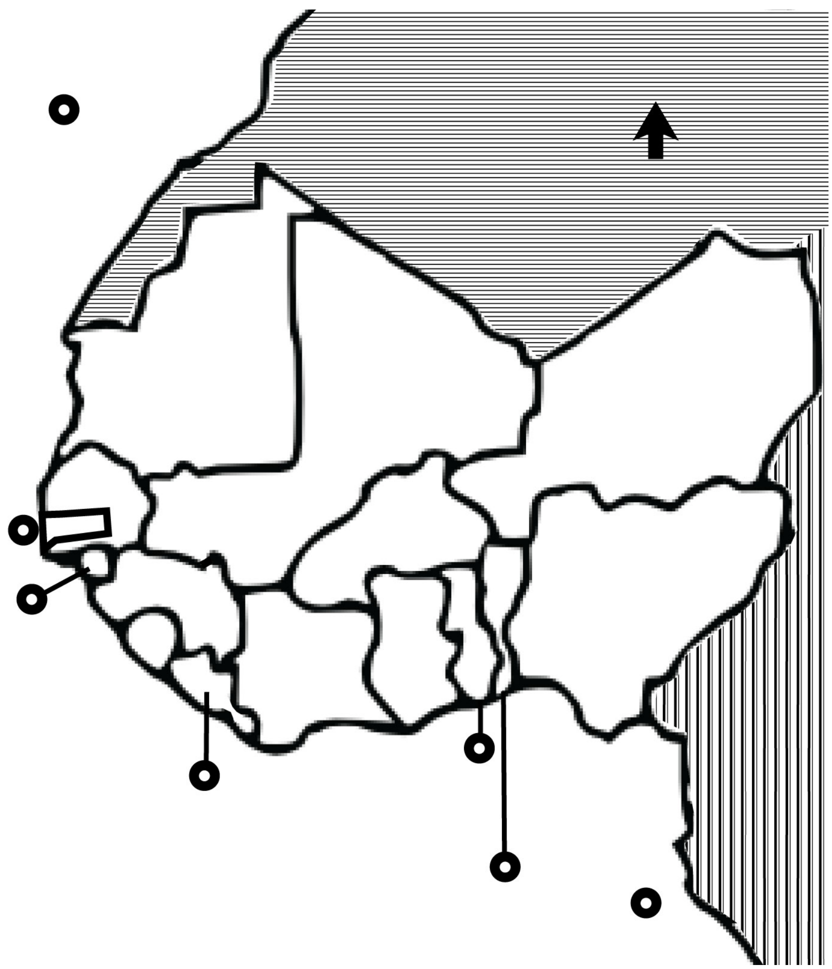

Figure C.8: Week 2 Graphics

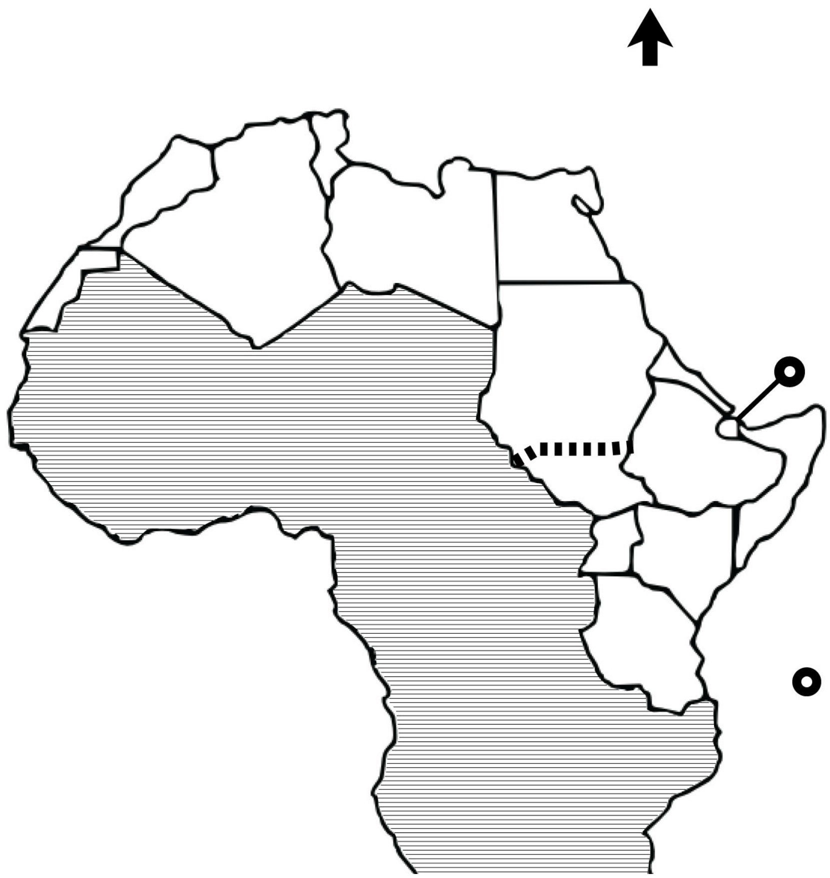

Figure C.9: Week 2 Graphics

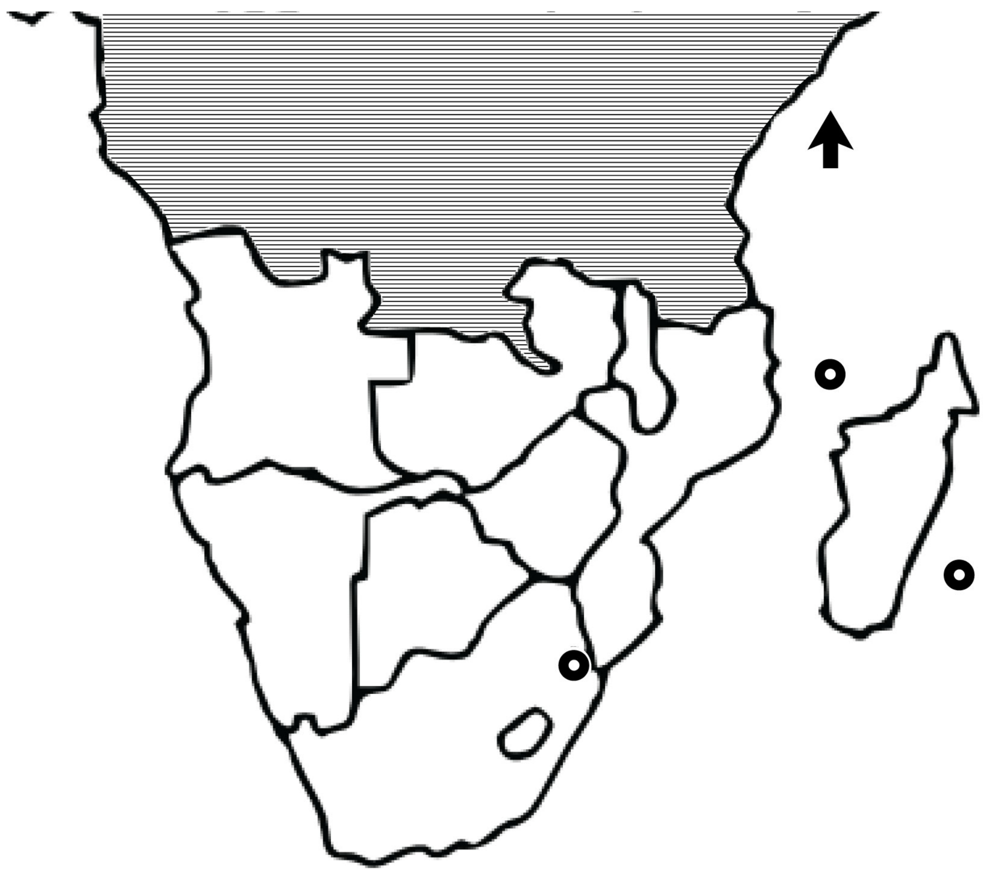

Figure C.10: Week 2 Graphics

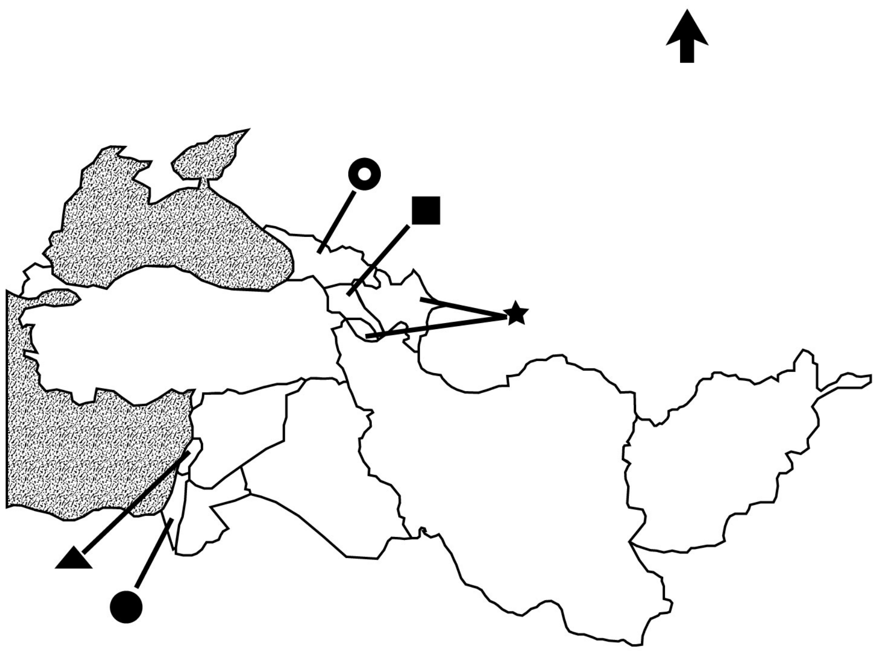

Figure C.11: Week 3 Graphics

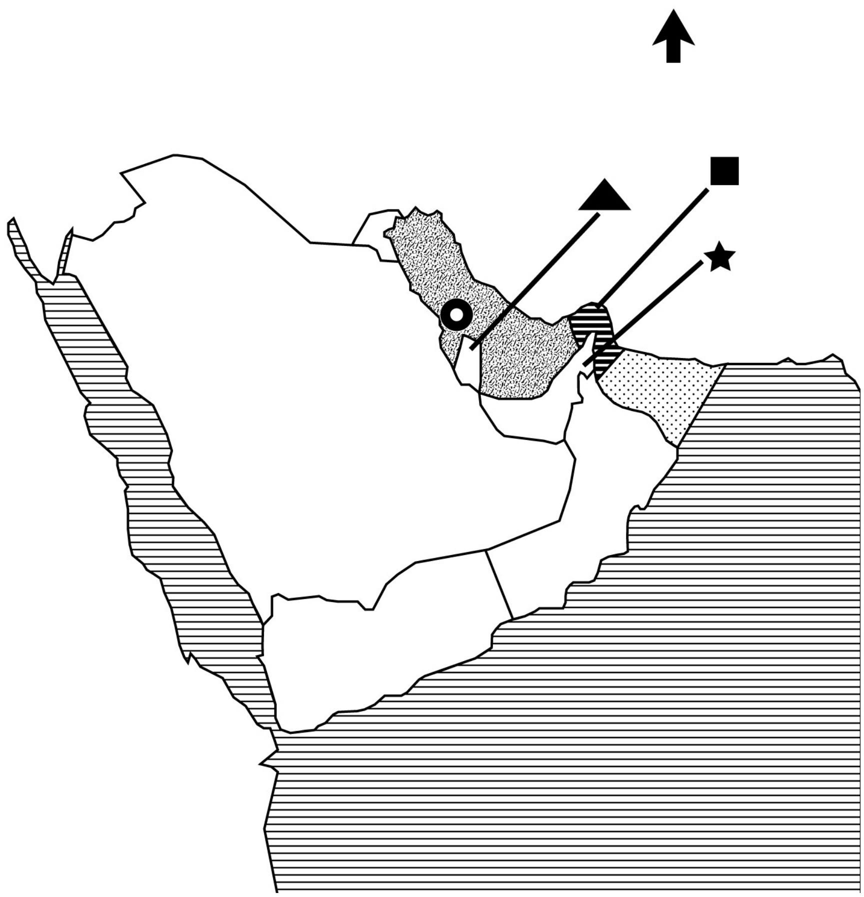

Figure C.12: Week 3 Graphics

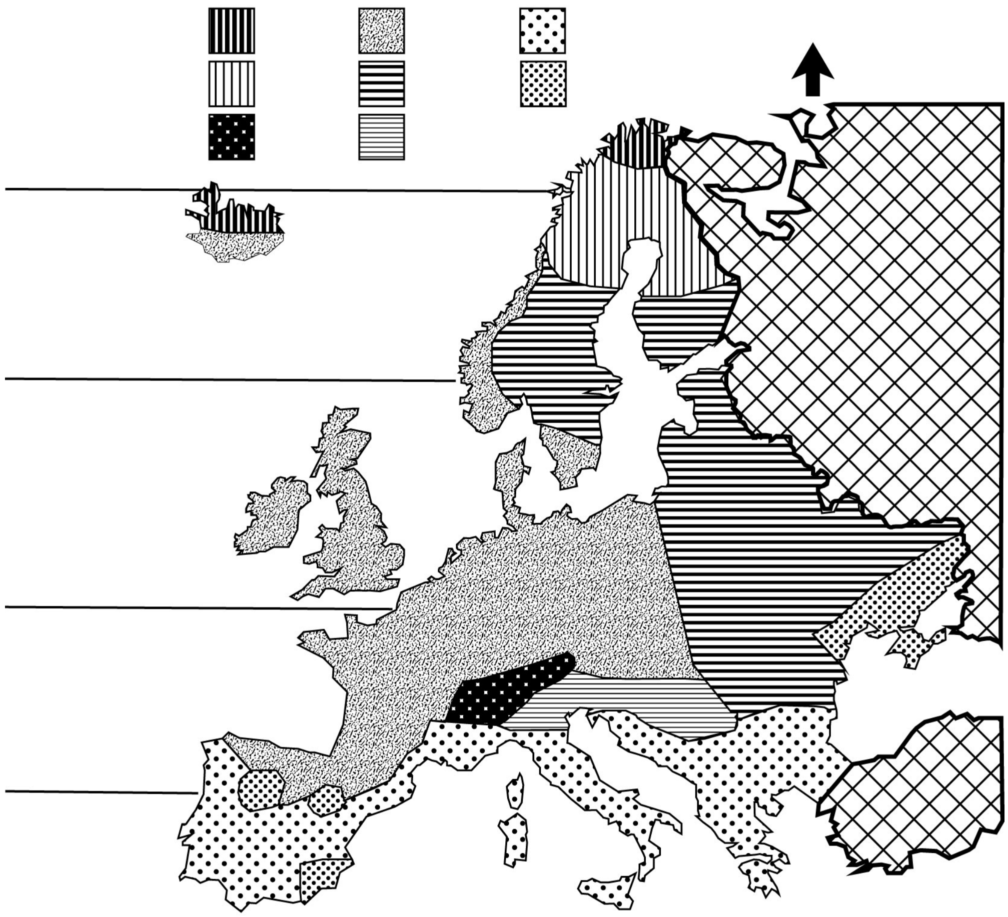

Figure C.13: Week 4 Graphics

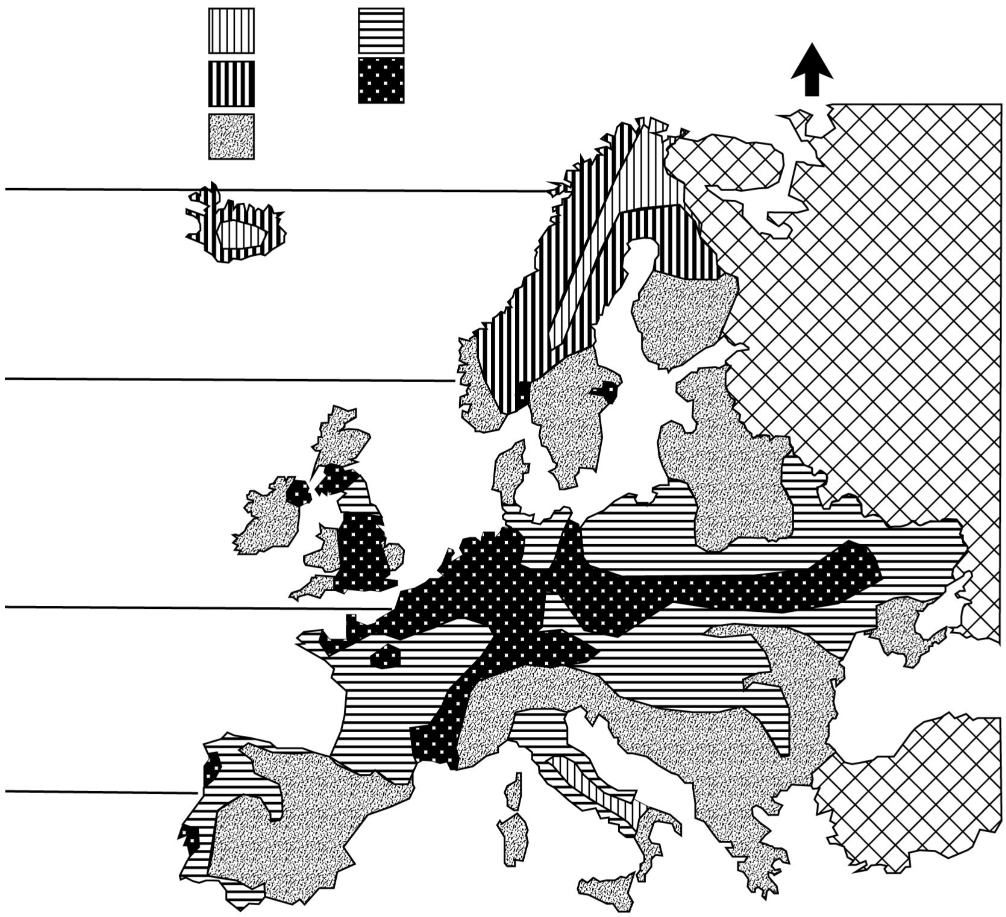

Figure C.14: Week 4 Graphics

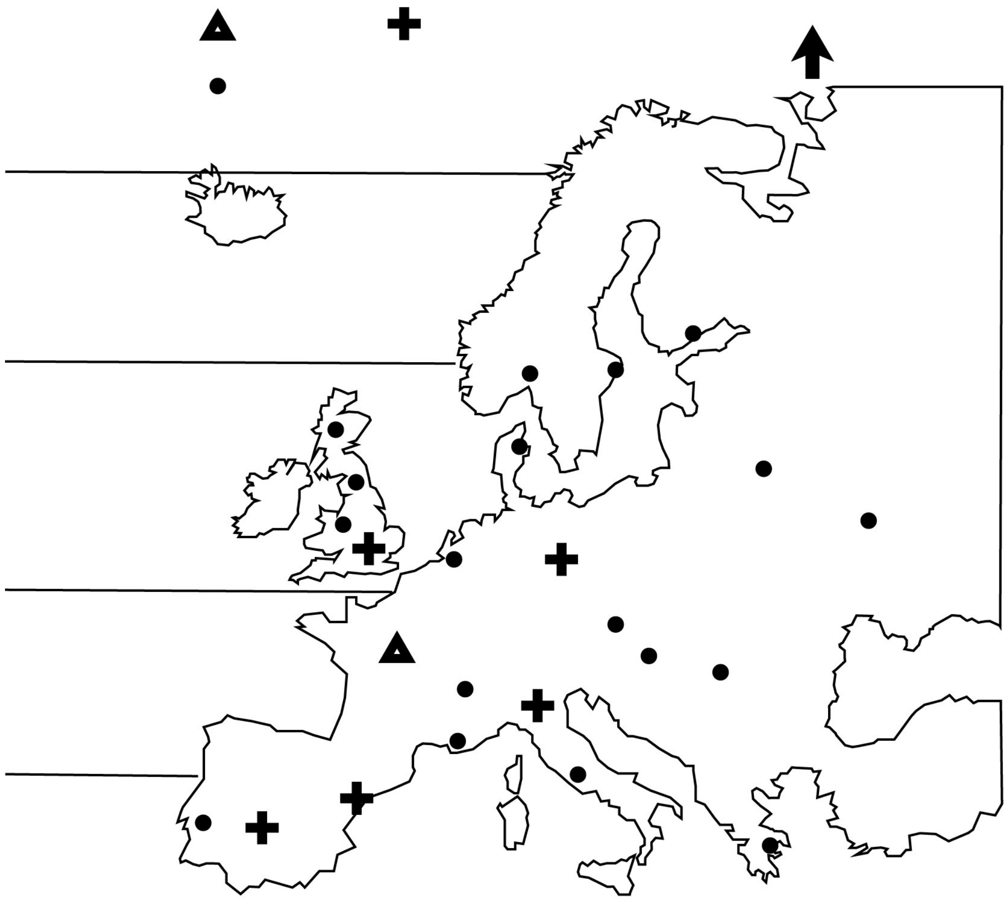

Figure C.15: Week 4 Graphics

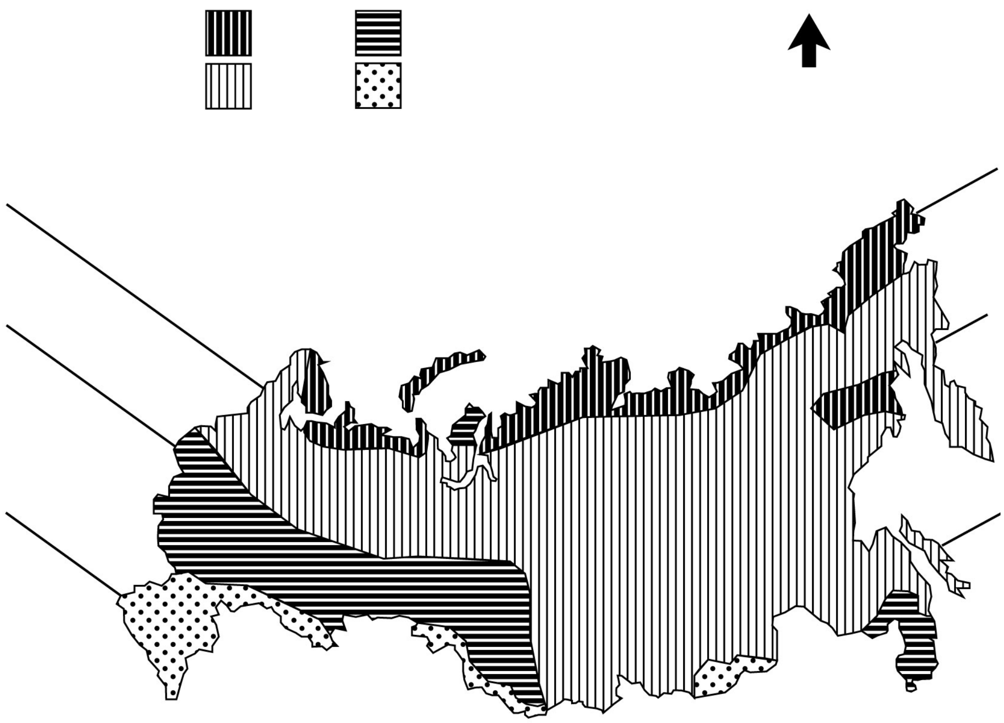

Figure C.16: Week 4 Graphics

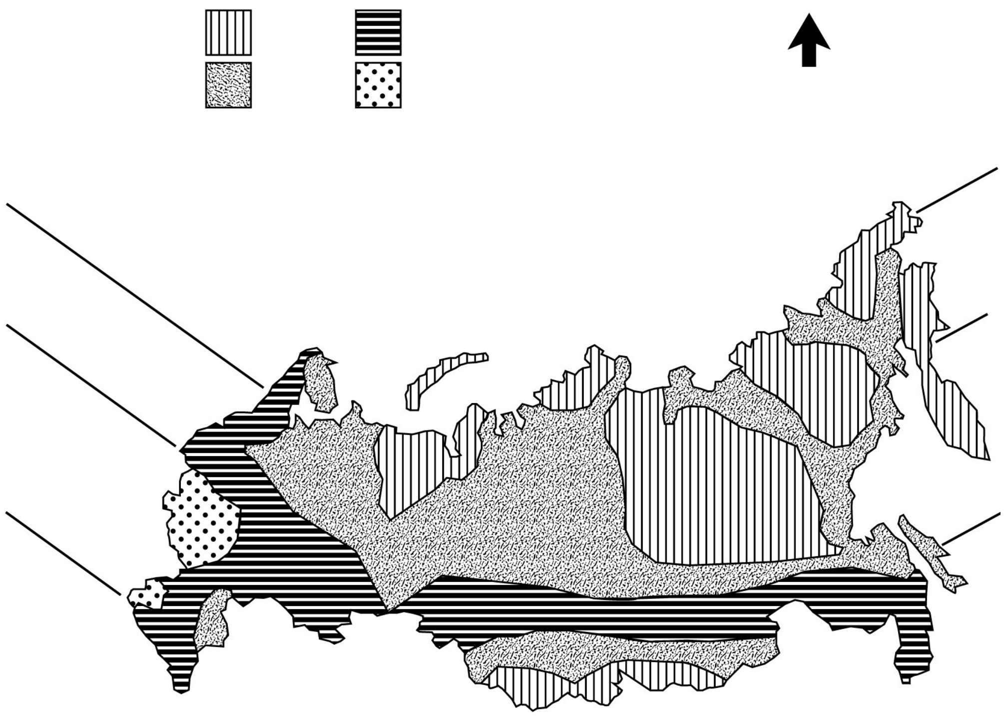

Figure C.17: Week 4 Graphics

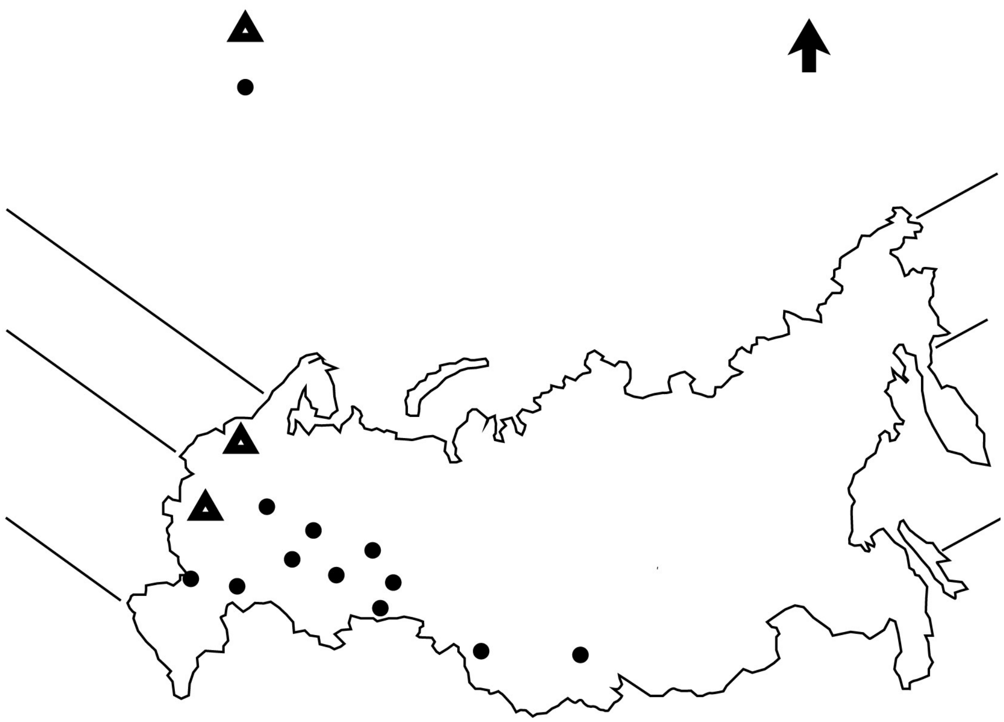

Figure C.18: Week 4 Graphics

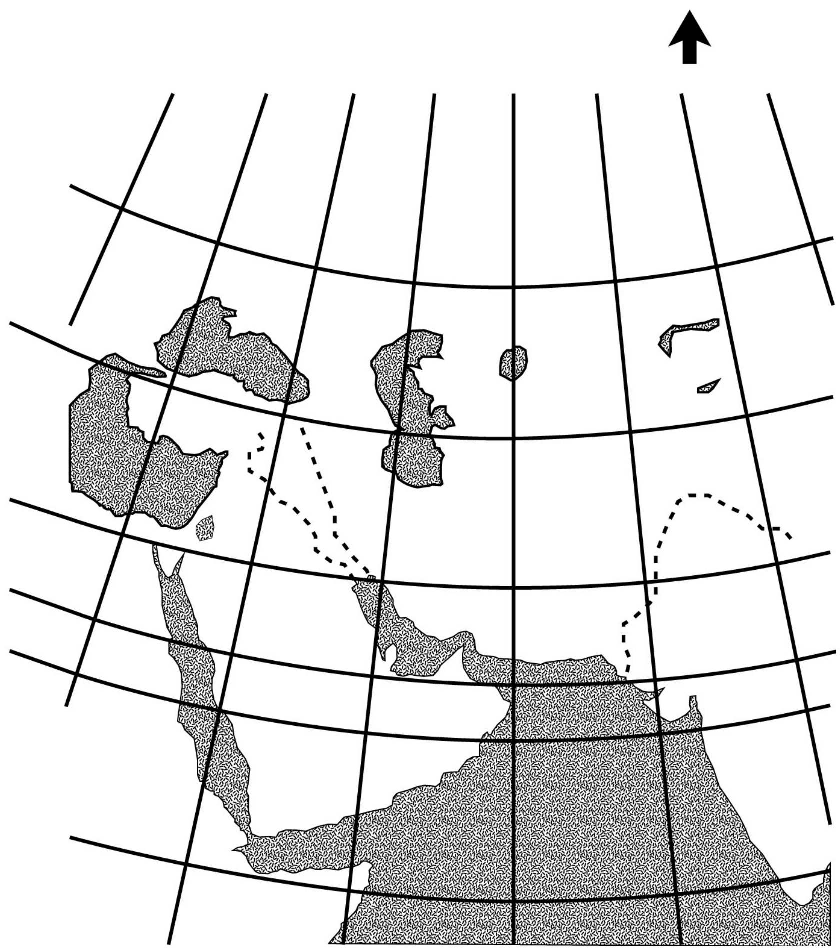

Figure C.19: Week 5 Graphics

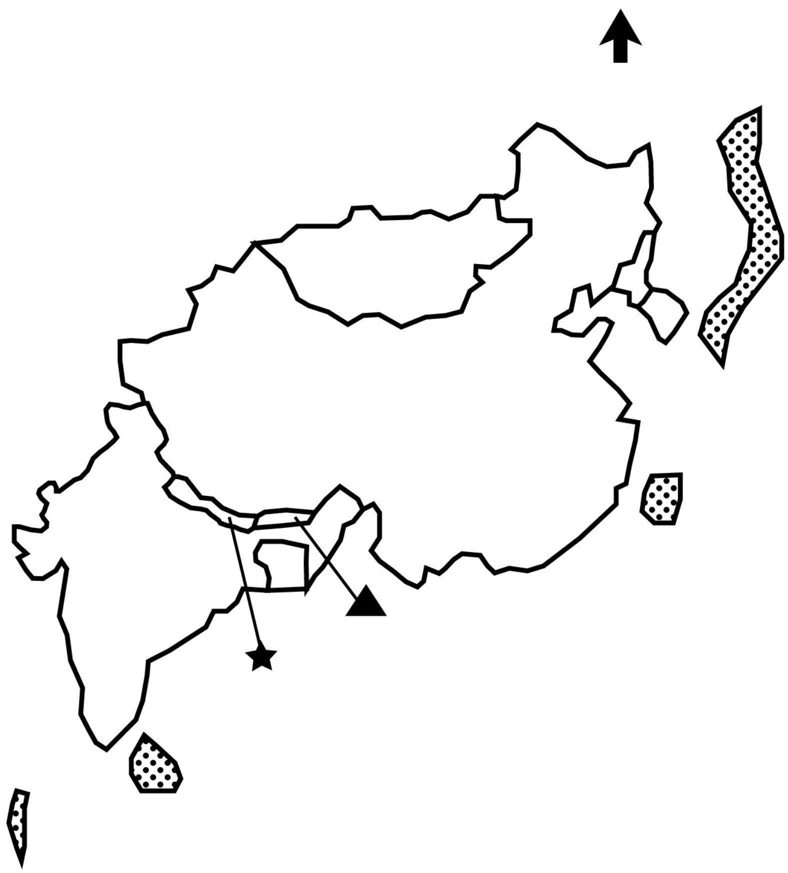

Figure C.20: Week 6 Graphics

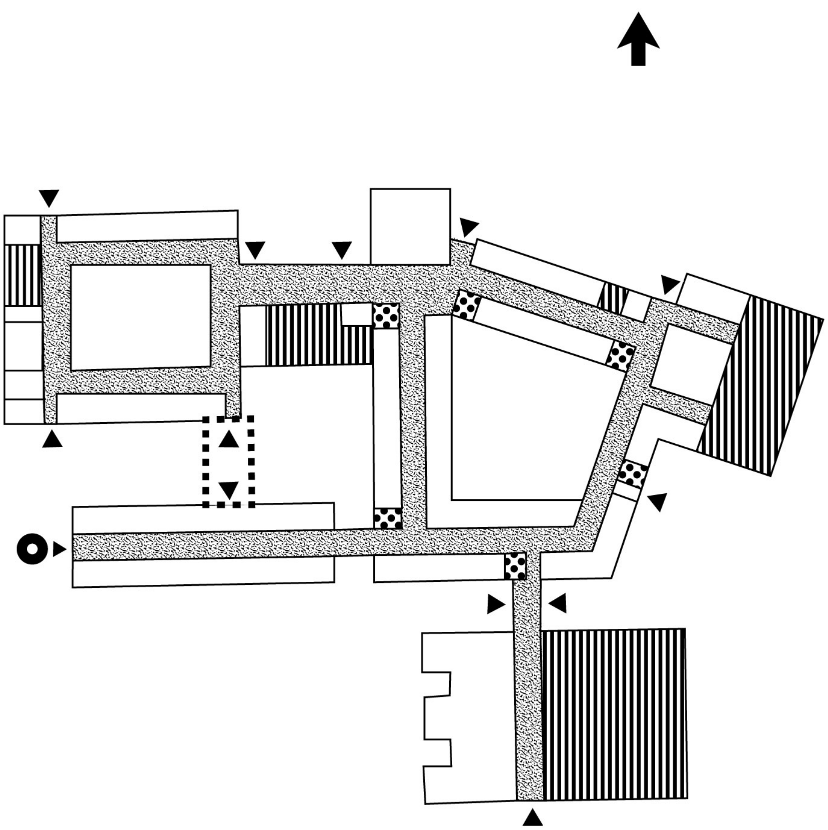

Figure C.21: Week 1 and 2 Graphics

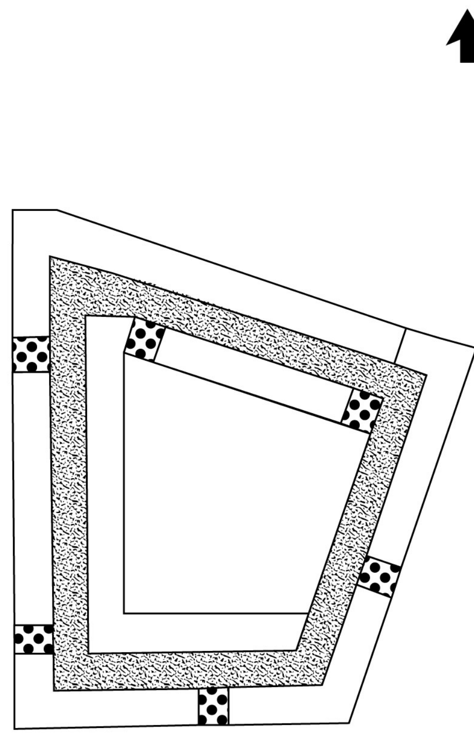

Figure C.22: Week 1 and 2 Graphics

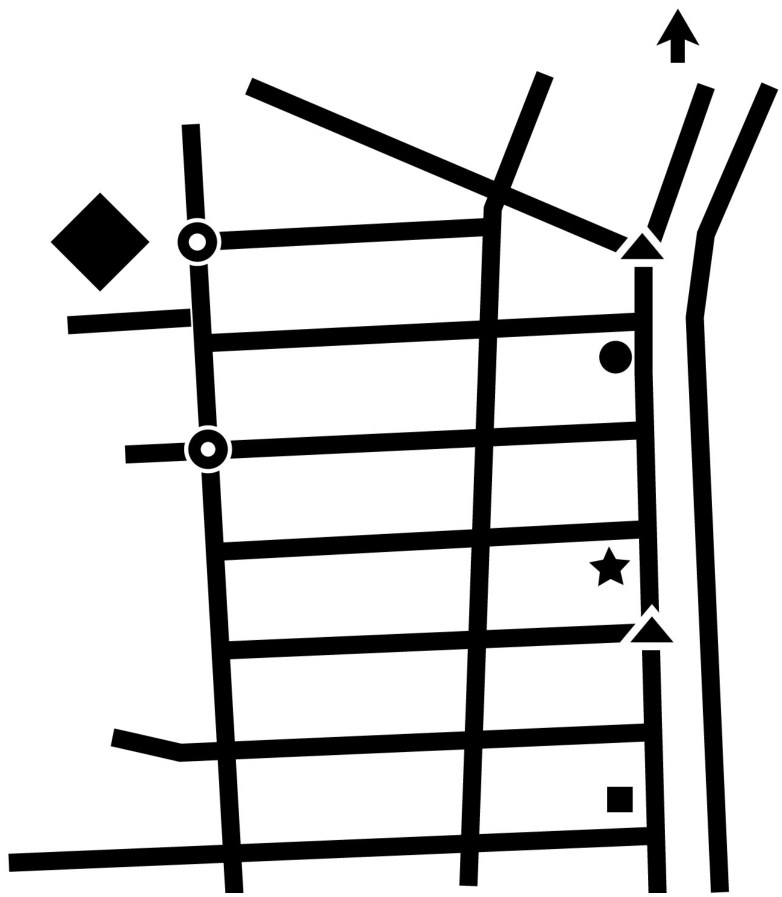

Figure C.23: Week 5 and 6 Graphics

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