LEVERAGING DYNAMIC AUDIO-TACTILE USER INTERFACES TO ENABLE BLIND PERSONS TO ACCESS COMPLEX GRAPHICS

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ABSTRACT

Graphics are a fundamental part of our lives, shaping how we learn, communicate and understand the world, from basic educational graphs to complex neural network architectures. Individuals with blindness or visual impairment (BVI) still face significant challenges in accessing and understanding graphical information. While current assistive technologies, such as screen readers and single-line Braille readers, offer solutions for text accessibility, they remain insufficient for empowering BVI individuals to understand everyday graphical data, including charts, tables, web pages, images, diagrams, and floor plans.

Emerging technologies, such as tactile graphic readers and 2D refreshable tactile pin displays, have introduced innovative audio-tactile ways for presenting graphical data through tap-to-hear dynamic interaction and real-time refreshable pin representations. Despite significant advancements in hardware development, progress in user interface (UI) design has not progressed likewise. Related literature on user interface design has predominantly addressed interaction with simpler graphical information and often theoretical scenarios, leaving the full potential of this technology to address complex challenges and real-world data largely unexplored. Such demanding tasks involve pinpointing elements in large 2D tactile surfaces (challenge 1), exploring complex line charts (challenge 2), and learning complex travel routes in large network maps (challenge 3). Unlocking the potential of these emerging technologies requires innovative user interface solutions that empower blind and visually impaired individuals to navigate and understand complex tactile graphics independently and efficiently.

This research addresses these three critical challenges by designing and evaluating tailored audio-tactile user interfaces that leverage the capabilities of tactile graphic readers and 2D refreshable displays to improve graphics accessibility for BVI users. To develop these user interfaces, we adopt a human-centred, participatory design methodology that actively involves BVI users throughout all stages of the process, supported by iterative user testing for evaluation and validation. For each challenge, we design and compare several UI solutions using a combined quantitative and qualitative approach that applies well-established evaluation tools such as SUS and NASA-TLX, along with semi-structured interviews to assess key aspects. We validate our solutions and derive meaningful insights through statistical analyses, employing repeated measures ANOVA, Wilcoxon signed-rank tests, and Friedman tests.

In all addressed graphics accessibility challenges, the designed user interfaces consistently achieve meaningful improvements over state-of-the-art solutions, demonstrating their effectiveness, usability, and potential for real-world impact. For pinpointing elements in tactile surfaces, the Sonoice user interface, combining sonification with voice, offers an efficient, superior solution that adapts to natural diagonal hand movements and performs consistently well across both simple and complex tactile graphics. Key user interface features for exploring complex line charts effectively include using a musical instrument environment to help users correlate multiple lines simultaneously and responsive audio line tracing to help users learn each line's shape, peaks, troughs, and boundaries. To learn complex travel routes in network maps, a customizable, immersive 2D tactile interface best enables users to follow routes phase by phase through responsive line tracing, explore line nodes and beacons through structured audio-tactile feedback, and filter relevant audio information. Overall, this dissertation delivers innovative and scalable user interface solutions that significantly empower BVI users to access and interpret complex graphical data. It highlights the pivotal role of tailored user interface design in unlocking the full potential of 2D refreshable tactile displays and tactile graphic readers. Beyond advancing accessibility research, these solutions establish new benchmarks in audio-tactile interaction, with the potential to transform the design and experience of such information across multiple domains.

ZUSAMMENFASSUNG

Grafiken sind ein grundlegender Bestandteil unseres Lebens und prägen, wie wir lernen, kommunizieren und die Welt verstehen – von einfachen Lerngrafiken bis hin zu komplexen Architekturen neuronaler Netzwerke. Blinde Menschen und Menschen mit Sehbehinderung haben jedoch immer noch erhebliche Schwierigkeiten, grafische Informationen zu erfassen und zu verstehen. Während aktuelle Hilfstechnologien wie Screenreader und Braillezeilen den Zugang zu reinem Text ermöglichen, reichen sie nicht aus, um blinden und sehbehinderten Personen das Verständnis alltäglicher grafischer Daten wie Diagramme, Tabellen, Webseiten, Bilder, Schaubilder und Grundrisse zu ermöglichen.

Neue Technologien, wie taktile Grafiklesegeräte und zweidimensionale-taktile Pin-Displays, bieten innovative audio-taktile Möglichkeiten, grafische Daten durch „Tippen zum Hören" und dynamische Interaktion sowie Echtzeit-Aktualisierung der Pins darzustellen. Trotz erheblicher Fortschritte in der Hardwareentwicklung hinkt das Design der Benutzeroberflächen bisher hinterher. Die wissenschaftliche Literatur zur Gestaltung von Benutzeroberflächen befasst sich überwiegend mit der Interaktion einfacher grafischer Informationen und theoretischen Szenarien, sodass das volle Potenzial dieser Technologie zur Bewältigung komplexer Herausforderungen und realer Daten weitgehend unerforscht bleibt. Zu diesen anspruchsvollen Aufgaben gehören das gezielte Auffinden von Elementen auf großen zweidimensional-taktilen Oberflächen (Herausforderung 1), das Erkunden komplexer Liniendiagramme (Herausforderung 2) und das Erlernen komplexer Routen in großen Liniennetzplänen (Herausforderung 3). Um das Potenzial dieser neuen Technologien zu erschließen, sind innovative Benutzeroberflächen erforderlich, die blinde und sehbehinderte Menschen befähigen, komplexe taktile Grafiken eigenständig und effizient zu erfassen und zu verstehen.

Dieses Werk beschäftigt sich mit diesen drei zentralen Herausforderungen, indem maßgeschneiderte audio-taktile Benutzeroberflächen entwickelt und bewertet werden, die die Fähigkeiten taktiler Grafiklesegeräte und zweidimensional-taktiler Displays nutzen, um die Zugänglichkeit von Grafiken für blinde und sehbehinderte Nutzer zu verbessern. Zur Entwicklung dieser Benutzeroberflächen verwenden wir eine nutzerzentrierte, partizipative Designmethode, die blinde und sehbehinderte Nutzer aktiv in alle Phasen des Prozesses einbindet und durch iterative Nutzertests zur Evaluation und Validierung unterstützt wird. Für jede Herausforderung entwerfen und vergleichen wir mehrere Lösungen für Benutzeroberflächen und verwenden dabei einen kombinierten quantitativen und qualitativen Ansatz mit bewährten Evaluationsinstrumenten wie SUS und NASA-TLX sowie halbstrukturierten Interviews zur Ermittlung wichtiger Aspekte. Unsere Lösungen validieren wir durch statistische Analysen, unter Einsatz von Verfahren wie der Varianzanalyse mit ANOVA, dem Wilcoxon-Test und dem Friedman-Test, um aussagekräftige Erkenntnisse zu gewinnen.

In allen behandelten Herausforderungen des Zugangs zu Grafiken erzielen die entworfenen Benutzeroberflächen durchweg erhebliche Verbesserungen gegenüber dem Stand der Forschung und zeigen damit ihre Effektivität, Benutzerfreundlichkeit und das Potenzial für reale Anwendungen. Für das präzise Auffinden von Elementen auf taktilen Oberflächen bietet der Sonoice-Ansatz, der Sonifikation mit Sprache kombiniert, eine effiziente und herausragende Lösung, die sich an die natürlichen diagonalen Handbewegungen blinder und sehbehinderter Menschen auf taktilen Grafiken anpasst und sowohl bei einfachen als auch komplexen taktilen Grafiken konstant gute Leistungen erbringt. Wesentliche Merkmale der Benutzeroberfläche zur Erkundung komplexer Liniendiagramme sind die Nutzung einer musikalischen Instrumentenumgebung, die den Nutzern hilft, mehrere Linien zu ertasten und zu verfolgen, sowie ein reaktives Audio-Linienverfolgungssystem, das das Erlernen der Form, Spitzen, Täler und Grenzen jeder Linie unterstützt. Das Erlernen komplexer Routen in Liniennetzplänen ermöglicht den Nutzern am besten ein anpassbarer, immersiver zweidimensional-taktiler Ansatz. Hierbei werden Routen schrittweise mittels reaktiver Linienverfolgung erkundet, Linienknoten und Beacons durch strukturierte audio-taktile Rückmeldungen erkundet und relevante Audioinformationen gefiltert. Insgesamt liefert diese Dissertation innovative und breit einsetzbare Ansätze für Benutzeroberflächen, die blinde und sehbehinderte Nutzer befähigen, komplexe grafische Daten zu erfassen und zu interpretieren. Sie unterstreicht die entscheidende Rolle eines maßgeschneiderten Designs der Benutzeroberfläche bei der Ausschöpfung des vollen Potenzials von zweidimensional-taktilen Displays und taktilen Grafiklesegeräten. Über die Fortschritte im Forschungsbereich assistiver Oberflächen hinaus, setzen diese Lösungen neue Maßstäbe in der audio-taktilen Interaktion und haben das Potenzial, das Design und die Nutzung solcher Informationen in vielfältigen Anwendungsbereichen grundlegend zu verändern.

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Part I.

BACKGROUND

1. INTRODUCTION

Graphics stand as a powerful tool for transforming complex, abstract data into clear 2D representations that reveal the identification of relationships, patterns, and trends that would otherwise be difficult to grasp. From simple educational graphics to complex neural network architectures, graphics serve as a tool not only for learning or communication but also for shaping our understanding of concepts, systems, and phenomena in both the natural and digital worlds. However, despite technological advances, individuals with blindness or visual impairment (BVI) continue to face significant challenges in accessing and understanding graphics. While standard assistive technologies like touch screen readers and single-line Braille readers improve text accessibility, they remain insufficient for empowering BVI individuals to understand and explore everyday graphical data, such as charts, tables, web pages, images, diagrams, and floor plans. Dynamic audio-tactile user interfaces (UIs) implemented on tactile graphic readers and 2D refreshable tactile pin displays have the potential to revolutionize graphic accessibility. Yet, existing research has not fully addressed all challenges, underscoring the need for tailored UI design. Furthermore, much of the work in this field remains conceptual, lacking application and validation with real-world complex graphics. This dissertation is centred on designing and leveraging dynamic audio-tactile UIs to empower BVI individuals in interpreting and exploring complex graphics grounded in specific challenge domains, driving the evolution of assistive technology and advancing accessibility in the representation and perception of graphical data.

1.1. MOTIVATION: ACCESS TO COMPLEX GRAPHICS

According to 2021 reports, over 2.2 billion people worldwide experience some form of vision impairment, with approximately 43.28 million being blind (visual acuity worse than 3/60) [3, 62]. In Europe, the European Blind Union (EBU) and WHO estimate that over 2.55 million people are severely visually impaired (visual acuity between 3/60 and 6/60) or blind, with a concerning unemployment rate of over 75% among working-age individuals with vision loss [3, 2]. In Germany alone, around 348,000 people are blind or severely visually impaired (BVI), according to 2021 Federal Statistical Office reports [41]. A critical factor contributing to this high unemployment rate is the limited access to graphical information in standard user interfaces. BVI people face challenges in perceiving and interacting with more complex graphical data such as images, graphs, tables, flow charts, formulas, web pages, and floor plans.

Assistive technology plays a crucial role in improving BVI individuals' ability to access and engage with digital and visual information. Among these technologies, single-line Braille readers are used worldwide by BVI individuals to access digital information through refreshable pin-raised tactile Braille characters. Typically, these devices are paired with screen readers, which use text-to-speech software to enable BVI users to operate with computers and smartphones. However, while essential for text-based data, these technologies fall short when it comes to conveying complex graphical data, limiting BVI individuals' access to visual information such as charts, graphs, and other two-dimensional content [165, 206, 276, 118]. To access complex graphical information, BVI individuals often turn to tactile representations, such as Braille-embossed and swell paper graphics, enabling them to engage with two-dimensional data through touch [99]. However, while these methods offer a valuable means of interaction, they are inherently limited in their capacity to represent more realistic and complex graphical concepts, such as charts, tables, web pages, images, diagrams, maps, and floor plans.

Innovative technologies, such as tactile graphic readers and 2D refreshable tactile pin displays, are transforming the landscape of assistive technology by offering dynamic audio-tactile user interface solutions for presenting complex graphical data. Tactile graphic readers aim to merge the tactile perception of embossed graphics with dynamic, context-driven audio feedback, allowing users to physically explore complex data while receiving detailed, real-time auditory descriptions that bring the graphical elements to life. 2D refreshable tactile pin (2DRTP) displays surpass the limitations of single-line Braille readers by offering a matrix of refreshable pins(raised up and down), offering a dynamic tactile experience alongside audio feedback, allowing BVI users to engage with both touch and sound to explore content actively. A significant amount of effort has historically been dedicated to improving the hardware of these technologies [308, 68, 306]. While many devices were developed in both academic and industrial sectors, most did not progress beyond prototypes, and many commercially available ones have either failed or been discontinued in recent years, mainly due to their high cost [237].

Dynamic audio-tactile user interfaces (through tactile graphic readers and 2DRTP displays) have great potential to transform assistive technology, yet further design advancements are crucial to unlock their capabilities fully. While past literature has addressed graphic access challenges, it has mainly focused on basic, straightforward graphics, leaving access to more complex, real-world graphical data largely unexplored. Investigating how dynamic audio-tactile UIs can empower BVI individuals to engage with complex graphics is crucial for promoting equal access and inclusion, advancing assistive technologies, and fostering a more equitable society in a visually-dominant world.

To fully harness the potential of these interfaces, UI design must be grounded in the specific graphic accessibility challenges inherent to different domains, effectively addressing the unique complexities of each context.

1.2. DISSERTATION CONTRIBUTIONS AND ROADMAP

In this dissertation, we explore three key challenges in graphics accessibility for BVI individuals: (1) finding and pinpointing elements on 2D tactile surfaces, (2) learning and exploring line charts, and (3) learning and exploring travel routes. We tackle these at their most demanding and realistic levels, defining the following research questions:

RQ1: How can dynamic audio-tactile UIs be leveraged to assist BVI individuals in pinpointing elements in large 2D tactile surfaces?

RQ2: How can dynamic audio-tactile UIs be leveraged to assist BVI individuals in learning and exploring complex line charts?

RQ3: How can dynamic audio-tactile UIs be leveraged to assist BVI individuals in learning and exploring complex travel routes in large network maps?

To address the research questions (RQ), we designed and evaluated dynamic audio-tactile user interfaces, utilising tactile graphic readers and 2DRTP displays. We used a human-centred, participatory approach throughout the design process, involving BVI users at every stage, from initial software design to later evaluations. This approach involved multiple UI design iterations and conducting usability studies to validate such iterations with BVI users in real-world scenarios. Figure 1.1 provides an overview of this dissertation's contribution and the methodology employed. Each research question was split into manageable sub-questions to focus on investigating different aspects of the challenge.

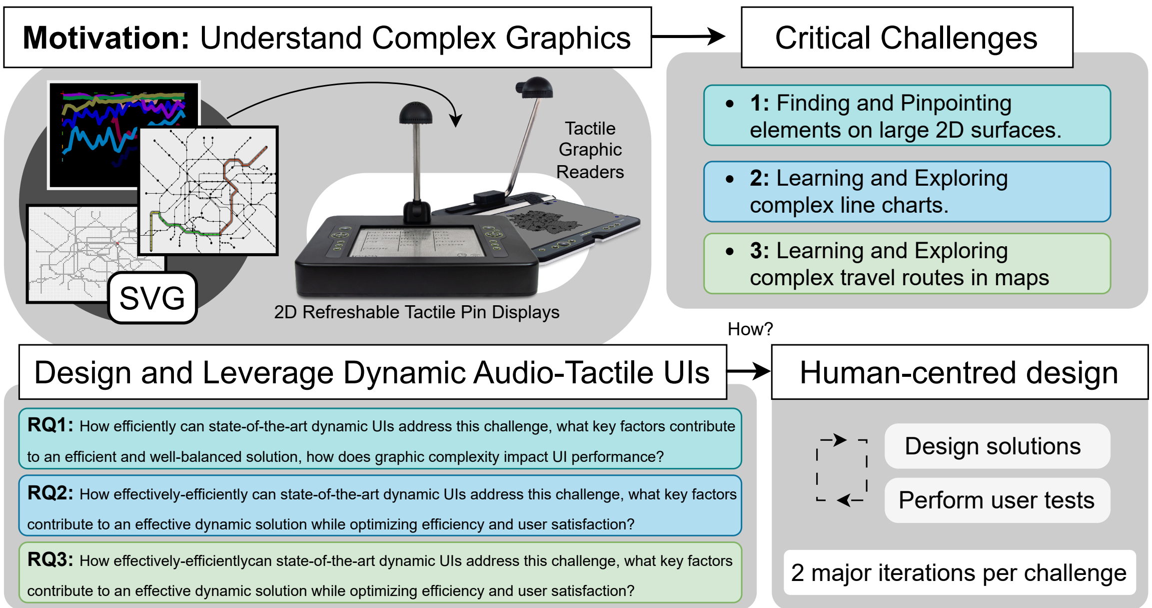

Figure 1.1.: Overview of dissertation contributions and research methodology

Pinpoint Navigation

Pinpointing elements on large tactile surfaces poses significant challenges for individuals with BVI who access 2D data. In chapter 4, which builds on two publications—MDPI (2022) [240] and Frontiers in Rehabilitation Sciences (2024) [241]—we investigate how to tackle this challenge by addressing the following sub-research questions:

RQ1.1: To what extent can current state-of-the-art audio-tactile UIs assist BVI individuals in efficiently pinpointing elements on large 2D tactile surfaces?

RQ1.2: What key design factors contribute to an efficient, well-balanced dynamic audio-tactile UI for assisting BVI users in pinpointing elements on large 2D surfaces?

RQ1.3: How does graphic complexity impact the performance and effectiveness of pinpoint navigation user interfaces?

These sub-research questions were addressed through the investigation, design, and implementation of dynamic user interfaces employed on Tactile Graphic Readers. This process followed a human-centred, participatory design approach, leading to two HCD iterative cycles, detailed in sections 4.2 and 4.3. Additionally, section 4.1 addresses the method-interface spectrum on assisting BVI individuals in pinpointing elements on large surfaces.

The first iteration investigated three dynamic pinpoint-navigation user interfaces: Sonar (proximity-radar sonification), Voice (clock-based speech instructions), and Axis (a newly proposed method using x- and y-axis sonification) - section 4.2. A user study with 13 BVI participants evaluated these interfaces on large A3 tactile graphics [240]. Results showed that the Axis method underperformed in efficiency and user satisfaction. Qualitative feedback highlighted difficulties in maintaining straight-line fingertip movements, which the Axis UI requires. While both Voice and Sonar performed well, there was no clear winner; Voice was faster, but users preferred Sonar.

Building on insights from the first study and employing a human-centred, participatory design approach, a novel method, Sonoice (Sonar + Voice), was developed to address such limitations by combining speech instructions with sonification - section 4.3. This second iteration was evaluated in a user study with 10 BVI participants, comparing Sonar, Voice, Sonoice, and the state-of-the-art trial-and-error approach on large A3 graphics [241]. Sonar, Voice, and Sonoice outperformed trial-and-error in both efficiency and satisfaction, demonstrating scalability across assistive technologies and robustness across varying graphic complexities. Sonoice achieved the highest efficiency, while most users preferred Sonar. Notably, users' preferences did not always align with their most effective UI, underscoring the importance of accommodating individual preferences and contextual factors when selecting a UI.

Line-Chart Exploration

While line charts are fundamental for visualising trends and comparing large amounts of data, individuals with BVI still face significant challenges in interpreting and exploring them, especially when dealing with complex charts containing multiple intersections and lines. In chapter 5, which is based on an *PETRA* 2023 publication [239]—we investigate how to tackle this challenge by addressing the following sub-research questions:

RQ2.1: To what extent can current state-of-the-art audio-tactile UIs assist BVI individuals in efficiently and effectively learning and exploring line charts?

RQ2.2: What key design factors contribute to an effective dynamic audio-tactile user interface for assisting BVI individuals in learning complex line charts while optimizing both efficiency and user satisfaction?

These sub-research questions were explored through the investigation, design, and implementation of dynamic audio-tactile user interfaces on Tactile Graphic Readers. The process adhered to a human-centred, participatory design approach, leading to two HCD iterative cycles, discussed in sections 5.2 and 5.3. Section 5.1 delves into the method-interface spectrum for assisting BVI individuals in learning and exploring line charts while also presenting the user interfaces designed and investigated in this dissertation.

A preliminary user study with four BVI participants was conducted to systematically evaluate the state-of-the-art tap-to-hear exploration UI for line chart exploration, compared to a proposed dynamic trigger-line tracing UI [239] - section 5.2. No significant differences were observed in efficiency, effectiveness, or satisfaction, and both UIs struggled to assist BVI in learning more complex charts. Participants highlighted difficulties in interpreting intersections and overlapping lines.

To address these challenges, a novel dynamic UI, 3-fold line-chart exploration, was developed and evaluated against the tap-to-hear UI in a study with 10 BVI participants using complex, realistic line charts - section 5.3. The 3-fold UI significantly outperformed tap-to-hear in efficiency, effectiveness, and satisfaction, empowering BVI users to access complex data and highlighting the importance of tailored user interface design grounded to specific contexts.

Map-Route Exploration

Effective pre-travel route planning is crucial for independent mobility. Learning travel routes on 2D maps is necessary for this process, yet it remains particularly challenging for individuals with BVI, especially when exploring large maps and complex routes. In chapter 6, which is based on an *PETRA* 2023 publication [238]—we investigate how to tackle this challenge by addressing the following sub-research questions:

> **RQ3.1:** To what extent can current state-of-the-art audio-tactile UIs help BVI individuals efficiently and effectively learn and explore travel routes in network maps?

> **RQ3.2:** What key design factors contribute to an effective dynamic audio-tactile user interface for assisting BVI individuals in learning complex map routes while optimising both efficiency and user satisfaction?

The exploration of these sub-research questions involved the investigation, design, and implementation of dynamic audio-tactile user interfaces on 2D Refreshable Tactile Pin Displays. This process followed a human-centred, participatory design methodology, leading to two HCD iterative cycles, which are examined in sections 6.2 and 6.3. Section 6.1 investigates the method-interface spectrum for supporting BVI individuals in learning and navigating travel routes while also showcasing the user interfaces developed and tested in this dissertation.

Building upon past literature, a tap-to-hear-based map exploration UI for 2D refreshable tactile pin displays [238] was implemented and evaluated in the context of learning metro network routes - section 6.2. A user study with 9 BVI participants revealed that the state-of-the-art tap-to-hear UI was insufficient for learning realistic, more complex routes.

To address this, a specialised UI, an immersive, dynamic map-route exploration UI, was developed and compared to tap-to-hear in a user study with 12 BVI participants for learning complex routes on large metro network maps - section 6.3. The immersive UI significantly outperformed tap-to-hear in efficiency, effectiveness, and satisfaction, enabling BVI users to learn real-world routes and advancing the potential of 2D refreshable tactile pin displays.

Dissertation Roadmap

Building upon these contributions, the remainder of this dissertation is organised as follows. Chapter 2 reviews prior work on dynamic audio-tactile user interfaces designed to support non-visual exploration of graphics, with a dedicated focus on 2DRTP displays, clarifying their terminology, key developments, and identifying design and interaction challenges that shape this emerging field. In Chapter 3, we describe the systems and devices employed to explore dynamic audio-tactile user interfaces for accessing complex graphical information, as well as the participatory, human-centred design methodology applied throughout this dissertation. Chapters 4, 5, and 6 address the core research questions of this dissertation by tackling three key challenges: pinpointing elements on 2D surfaces, exploring complex line charts, and learning complex travel routes, respectively. In each chapter, we review focused prior work related to the corresponding challenge, develop human-centred user interface solutions, and present significant user study findings involving BVI participants. Chapter 7 concludes the dissertation by summarising the main contributions and insights in advancing accessible, dynamic audio-tactile user interfaces

2. RELATED WORK

One never notices what has been done;
one can only see what remains to be done

Marie Skłodowska-Curie, 1894

Considerable research efforts have been dedicated to the development of assistive technologies for blind and visually impaired (BVI) individuals. Within the domain of graphics accessibility, two primary lines of contribution can be distinguished: one focuses on the transformation of visual information into accessible formats—either automatically or manually—while the other addresses how such information can be effectively conveyed to users through appropriate user interface design. This dissertation is centred on the latter, investigating and designing user interfaces to empower BVI individuals to interpret and leverage graphical information to its full potential. In this context, we adopt a user interface perspective and define the concept of dynamic audio-tactile user interfaces to set boundaries for design and development while establishing a clear framework for analysing audio-tactile and dynamic interactions.

A key technological foundation for this dissertation is the class of 2D refreshable tactile pin (2DRTP) displays and tactile graphic readers, which served as a baseline platform for implementing and designing dynamic audio-tactile UIs. Emphasis is placed on 2DRTP displays, which, despite continuous research since the 1990s, have been the subject of only a few literature reviews. Although they hold great potential to change how BVI users can access graphics, they are still emerging and remain largely absent from the daily lives of BVI users. This dissertation contributes to clarifying the terminology surrounding 2DRTP displays, offering a systematic analysis—including both current and discontinued projects—and presenting a comprehensive overview of their technical characteristics and audio-tactile interaction affordances. We also investigate the domain coverage of 2DRTP displays and their support for interactive UI elements. A detailed overview of the most prominent 2DRTP devices is provided in Appendix A.

Literature on tactile graphic readers is not extensively examined in this context but is incorporated within the UI spectrum for each addressed key challenge, as discussed in the subsequent chapters (see Sections 4.1, 5.1, and 6.1).

This chapter includes content from a publication in ICCHP 2022 [237].

2.1. USER INTERFACE SCOPE

Defining the scope of the user interface is fundamental to establishing the boundaries for evaluating and analysing the user interface aspects of 2DRTP displays. Additionally, clarifying the concepts of 'audio-tactile' and 'dynamic' interactions is essential for guiding the design of dynamic audio-tactile user interfaces and understanding their implications in each grounded context.

User Interface Interpretation

Authors present diverse interpretations and conceptualisations of user interface terminologies, leading to numerous proposed understandings of this concept [176]. Although the user interface is a key and common element in the Human-Computer Interaction (HCI) field, it still generates confusion surrounding its meaning and boundaries [177].

A user interface has been analogised to a pair of glasses, emphasising its capacity to reveal new perspectives and stimulate curiosity [39]. In contrast, another definition characterises traditional user interfaces as the boundary between system behaviour transducers (such as monitors and keyboards) and the user, explicitly excluding the software domain from the scope of the user interface itself [25]. Alternatively, the user interface has been conceptualised as the software component that facilitates and governs the communication between the user and the computer, effectively serving as an intermediary [211]. Other interpretations define the user interface as the computer system component through which users interact to perform specific tasks and achieve predefined objectives [280]. Furthermore, the HCI guidelines from the ACM SIGCHI Curricula position the user interface as the point of interaction and communication between humans and computers, encompassing an integrated approach that includes both hardware and software components [135].

This dissertation adopts the user interface definition established in ISO 9241:220:2019 (International Organisation for Standardisation) [146] while also drawing on the perspective provided by the HCI guidelines from the ACM SIGCHI Curricula [135], encompassing both hardware and software. According to ISO 9241:220:2019, user interface is:

> All components of an interactive system (software or hardware) that provide information and controls for the user to accomplish specific tasks with the interactive system.

This means that all components providing information and control to the user are considered part of the user interface. When discussing the various dynamic user interfaces developed in later chapters of this dissertation, these interfaces differ in that they incorporate additional or different components to deliver information and control for specific tasks, depending on the challenges addressed in each case.

Audio-Tactile Interaction

The terms "tactile" and "haptic" interaction are often used interchangeably in assistive technology, despite ongoing inconsistencies in their definitions (see ISO 9241-210:2019 [146]). While haptic broadly encompasses both tactile (cutaneous) and kinesthetic sensations [214, 65], most of the interactions relevant to this work involve surface exploration through the skin [257, 133]. Since both terms are valid and commonly used in the field (see ISO 9241-910:2011 [147]), this dissertation adopts "tactile" due to its greater specificity to skin-based sensing and its prevalence in related literature and device naming conventions (e.g., tactile displays, tactile graphic readers).

In most 2DRTP displays and tactile graphic readers, tactile interaction is complemented by audio feedback, creating a more immersive and intuitive user experience through multimodal (audio-tactile) interaction [308, 194, 110, 202, 197]. While tactile feedback relies solely on touch-based interaction, where users gather information through physical exploration of surfaces, audio feedback adds another dimension, incorporating audio tones, earcons, auditory icons, speech-based information, or 3d sounds. It is widely recognised that multimodal audio-tactile user interfaces, when carefully designed and implemented, can enhance the user experience by providing more intuitive and accessible ways of interaction [26, 160, 224, 136]. Moreover, multimodal interaction is often regarded as more natural because real-world interaction inherently involves multiple senses, making multimodality an inevitable and intuitive way of interaction [224]. Since audio interaction is commonly used but not mandatory in 2DRTP displays and tactile graphic readers, we did not include 'audio' when referring to these technologies, but used it exclusively to describe our developed UIs, all of which incorporate audio, classifying them as audio-tactile.

Dynamic Interaction (motion)

The term dynamic can be interpreted in various ways across assistive technologies. In this dissertation, dynamic interaction (motion) refers specifically to real-time feedback triggered by the user's active hand movement across a tactile surface. Our user interfaces continuously play audio in direct response to this movement, allowing users to explore structured content through motion-based auditory feedback.

This contrasts with other approaches sometimes called "dynamic," such as tactile displays with blinking pins or vibration feedback [232, 332, 148, 137, 10], or spatialized audio via headsets. These may provide real-time updates, but they do not necessarily rely on continuous, user-controlled exploration. Similarly, concepts like the "Braille mouse" (e.g., Virtouch) deliver localised tactile feedback against the skin via one or two Braille cells as the user moves the device. Although sometimes described as dynamic, this approach differs from continuous, active exploration, as tactile feedback is delivered passively during device movement, which has been demonstrated to reduce tactile performance and slow user interaction.

The user interfaces presented here enable active tactile perception through motion (hand movement) that is continuously augmented by auditory output, without using vibration or real-time pin actuation. This qualifies them as dynamic audio-tactile user interfaces, combining motion-driven interaction with real-time, auditory feedback.

2.2. A TOUCH OF INNOVATION: 2D REFRESHABLE TACTILE PIN DISPLAYS

Exploring 2D Refreshable Tactile Pin (2DRTP) displays holds significant scientific and social relevance (Figure 2.1). These displays enable innovative interaction paradigms and introduce a novel class of user interfaces to the scientific community. Their potential to improve the lives of visually impaired individuals by granting access to two-dimensional, dynamic information represents a groundbreaking advancement. Understanding the full scope of their contributions to user interface design and their broader impact requires systematic study and documentation. Such examination not only highlights the progress made but also identifies domains and user interfaces that warrant further development, guiding future research and innovation in the field of 2DRTP displays.

Figure 2.1.: Prominent 2D Refreshable Tactile Pin (2DRTP) Displays from Research and Market. This includes active (up to 2025) and discontinued projects/devices.

2.2.1. Uncovering 2DRTP Displays

Single-line Braille Displays have become indispensable tools for individuals with visual impairments, granting them access to textual information and fostering connections with the digital world. However, this technology is limited in its ability to represent graphical content, such as Excel sheets, math graphs, web browsers, maps, and more. To address this limitation, researchers worldwide scaled Single-line Braille Displays into 2D adaptations, marking the emergence of an innovative technology capable of conveying graphical information through tactile and audio feedback.

Before delving into the realm of these displays, it's crucial to define the boundaries of what constitutes a 2DRTP device. 2D Refreshable Tactile Pin Displays feature a refreshable tactile surface constituted by tactile pins (taxels). These tactile pins are arranged in a two-dimensional matrix, where each pin is raised and lowered at real-time speed. Most devices utilise binary positioning, where pins can only be fully raised or lowered. However, some devices offer multiple pin positions to enrich and provide more tactile details [244]. Beyond tactile feedback, specific devices incorporate audio feedback through sonification and speech to enhance graphical information [308]. 2DRTP displays have large screens enabling two-hand tactile exploration and permitting the perception of friction forces.

Regarding the nomenclature surrounding 2DRTP Displays, the landscape is diverse and multifaceted. Authors and literature have employed many different terminologies when addressing this technology. These include: 2D Braille Displays [329], Graphical Tactile Displays [68, 323, 244, 116], 2D Tactile Pin-Matrix Displays [48, 308], 2D Multiarray Braille Display [167, 168], Large Dynamic Tactile Displays [45], Full-Page Braille Displays [256], Refreshable Braille Display [332], Planar Tactile Displays [232], Braille Tablet Displays [8], Braille Pads [183], and Tactile Displays [265]. To encompass the maximum number of 2D Refreshable Tactile Pin (2DRTP) Displays, all of these nomenclatures were retained when exploring scientific and technical documentation of this technology.

For the sake of clarity and precision, we have chosen to use the term **2DRTP Displays** as our preferred nomenclature, accurately representing the diverse features and functionalities of these devices. '2D' denotes the display's two-dimensional nature, excluding single-line refreshable tactile displays. 'Refreshable' refers to the ability to update and modify the tactile output in real-time, distinguishing it from tactile graphics displays that lack this capability [181, 143, 117, 5]. The term 'tactile' is used instead of 'haptic' since this technology does not convey kinesthetic sensation but only tactile touch and cutaneous feedback [65]. 'Pin' conveys the immediate, clear idea that the tactile surface consists of small pins, distinguishing it from alternative tactile feedback mechanisms such as touch-based screens or shape-changing displays [101, 279]. Notably, the term 'braille', often used in "Single-line braille displays", is not used here since some of these devices cannot represent Braille text [244]. The term 'display' is used because the primary function of most devices is still to present information, even if some models are standalone and include their processing units and extra features.

Given the absence of concrete definitions and the varying terminologies employed by different authors, it is crucial to establish clear criteria that scope 2DRTP displays. In defining these requirements, guidelines proposed for Single-Line Braille Displays [256], Graphical Tactile Displays [306], and Braille formats [53] are taken into consideration. By incorporating these guidelines, we can create a comprehensive framework that outlines the essential features and functionalities of 2D refreshable tactile pin displays, including 2D pin layout, large surface area, real-time refresh, touch resistance force, friction-inducing, and perceptible pin height.

2D Pin-layout

The distinguishing characteristic between Single-line Braille Displays and 2D Refreshable Tactile Pin Displays lies in the arrangement of the tactile pins. In 2DRTP displays, the tactile pins are organised in a 2D layout to represent graphical information effectively. Contrarily, Single-line Braille Displays typically consist of only four rows of tactile pins, with three rows designated for braille characters and one row indicating the current keyboard position. Although this pin arrangement performs well for representing text [256], it is insufficient for conveying graphical information, as it lacks the necessary matrix structure. Hence, such displays cannot be considered 2DRTP Displays.

Large surface area

The effective representation of graphical information in 2DRTP displays is closely tied to the surface size. To ensure that small prototypes are not classified as 2DRTP displays, specific criteria have been established. These criteria focus on devices with a tactile surface larger than $120\,\text{cm}^2$ or equipped with more than 350 tactile pins (taxels). These standards underscore the significance of having a sufficiently wide tactile area, which not only enables enhanced graphical representation but also contributes to an improved user experience. Moreover, these criteria serve to encompass devices that not only offer enhanced graphical representation and an improved user experience but also ensure a tactile surface large enough to facilitate interaction with both hands.

Real-time refresh

The refreshable time rate is a crucial factor for 2DRTP Displays. The system must be capable of updating its tactile screen in real-time, ensuring a timely and predictable manner of refreshment. This is essential for the usability of the device as a refreshable interface for individuals with BVI. The longer it takes to refresh the whole matrix of pins, the less practical it is to represent dynamic graphical information. The specific refresh rate, measured in hertz (Hz), required for a system to be considered real-time varies depending on the application and context. While a standard video processing application may demand a frame rate of at least 30 Hz, this requirement does not hold true for 2DRTP Displays. Given the emerging nature of this technology, its refreshment rates vary significantly. To investigate a larger group of 2DRTP Displays in this analysis, the inclusion criterion is set to devices that have a refreshable rate of at least 0.03 Hz, indicating that they take up to 33 s to update the entire tactile pin surface.

Touch resistance force

The tactile pins must proportionate an acceptable and ample touch resistance force. Some users might exert a light touch force, while others may have a heavier fingertip reading touch. The system must ensure good uniformity in raised pins with hard-end-edged stop mechanisms to reach and include all users. According to the norms of single-line braille displays, the tactile pin should remain raised within 0.01 mm of its maximum raised-up height with a fingertip reading force of 5 g [256]. Despite being a disadvantageous aspect, the ability to raise the pins when the user rests their hand on the pin-matrix surface is not considered a critical UI feature of this technology. It's important to note that 2DRTP devices lacking this capability can still be classified as such, as they encompass numerous other essential user interface aspects [145, 164, 141].

Friction-inducing

The display must not be frictionless. Friction forces are vital when exploring tactile reliefs, especially on tactile pin-matrix surfaces. Devices with reduced display size, such as the remarkable reading aid OPTACON [190], cannot reproduce friction forces, which play a crucial role in facilitating tactile interaction for individuals with BVI [273, 306]. Consequently, such displays do not meet the criteria for being classified as 2DRTP Displays.

Perceptible Pin height

The technology must provide a noticeable difference between raised and non-raised pins that is perceptible by touch to any user. It is recommended that a non-raised pin should be positioned at least 0.25 mm bellow the reading surface, and a raised pin should raise between 0.5 and 0.9 mm above the surface [256, 53, 300]. Devices with multiple levels of pin elevation (not binary) were not excluded.

Figure 2.2 represents the concise overview of the criteria that shape 2DRTP Displays.

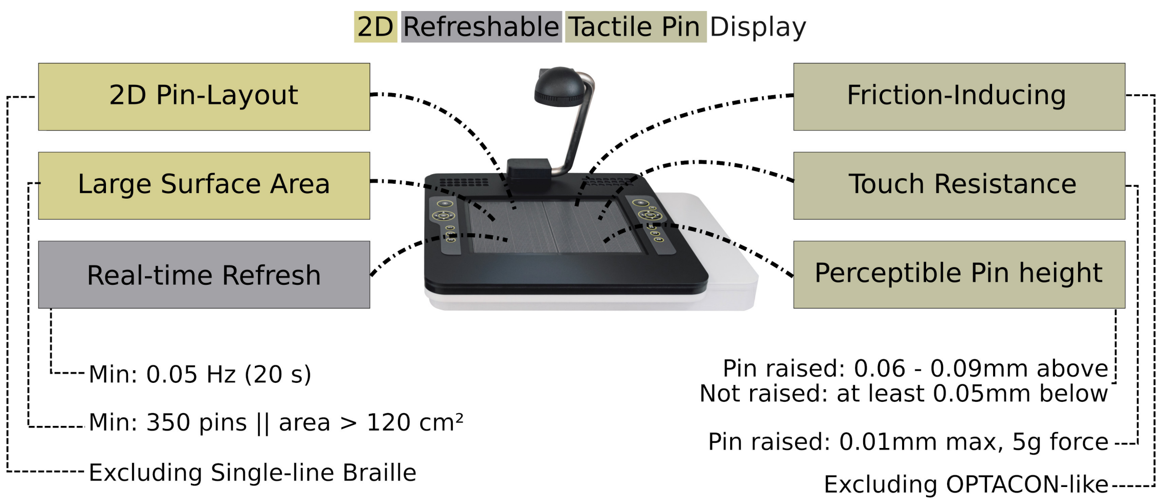

Figure 2.2.: Criteria for defining 2D refreshable tactile pin (2DRTP) displays

2.2.2. Evolution of 2DRTP Displays

2DRTP displays have risen as a groundbreaking assistive technology, offering innovative solutions to blind and visually impaired people. However, given their status as an emerging technology and their exclusive focus on a limited number of end-users, the availability of contributions in this field remains scarce and dispersed. To bridge this knowledge gap, a current and all-encompassing analysis of the state-of-the-art 2DRTP displays is essential. Prior to conducting an in-depth examination of individual displays, a preliminary look at past analyses and discussions related to 2DRTP displays was taken. With this, we broaden our knowledge of this domain, obtaining valuable insights into the technology's obstacles and research priorities before delving in-depth into each display.

Prior Overviews on 2DRTP Displays

Despite the limited availability of contributions in this domain, substantial advancements have been achieved through prior research reviews concentrated on 2DRTP displays and related technologies [68, 306, 268, 216, 227, 121, 45, 208, 324]. These endeavours have resulted in the advancement of this field, yielding intriguing findings and insights.

Between 2007 and 2008, comprehensive reviews of 2D refreshable tactile pin displays were conducted [68, 306]. The first 2DRTP displays (known as static-refreshable displays at the time) emerged, highlighting the initial recognition of their potential to address graphic accessibility issues. These displays featured large pin screens powered primarily by piezoelectric actuators or micro solenoids. Notable examples included the DMD-12060 display from METEC AG [266, 205], KGS devices (DV1 and DV2) [79, 80], the MIMIZU system (DV1 and DV2) [170, 313, 171], the GWP from Handy Tech GmbH [115], and the NIST display [251, 249]. The reviews also covered dynamic-refreshable displays, which are small, tactile screens attached to pointer devices that refresh their content as the pointer moves across a virtual image, including the pioneering OPTACON device [190], the VirTouch Mouse (VTM) [158], and the VITAL interface [27]. While these devices did not reproduce friction forces (and were thus not classified as 2DRTP displays), their development played a crucial role in advancing the field and 2DRTP displays. The analyses examined aspects such as screen size, refresh rates, resolution, and other hardware characteristics. Despite the emergence of initial 2DRTP displays and prototypes, the reviews concluded that 2DRTP displays were hindered by high power consumption and production costs, limiting their potential for widespread adoption and further development.

A few years later, between 2013 and 2015, reviews expanded upon earlier work, offering an updated overview that explored the potential benefits of 2DRTP displays to date [268, 216]. Besides the previously mentioned devices, these reviews also cited the prominent BrailleDis 9000 from Metec AG [308]. The analysis focus was on upcoming research topics in the field, including the integration of touch surfaces and gesture support, the exploration of suitable UI elements, and the development of adaptive levels of detail (conveying data in different details). Despite these advancements, the reviews concluded that the 2DRTP displays remained high-cost, limiting their access to the BVI community.

Between 2016 and 2020, significant projects and overview analyses updated the current state of 2DRTP displays [227, 121, 45]. The most pivotal advancement during this timeframe was the HyperBraille project, which not only designed several 2DRTP displays from Metec AG but also conducted extensive research on user interface design on 2DRTP displays, including the BrailleDis 6240 (also known as HyperBraille F Display) [49], the BrailleDis 7200 [42], the Hyperflat [8], and the Tactile2D [9]. Beyond the previously mentioned displays, other key 2DRTP displays were introduced during these years, including the Graille device from Tsinghua University [323], the Canute 360 from Bristol Braille Technology [291], the first version of the Graphiti from Orbit Research [244], and an early prototype that years later would become the Tactonom Pro from Inventivio GmbH [116]. Compared to previous literature reviews [68, 306], this period saw a remarkable increase in the number of devices, reflecting the continuous progress and advancements in 2DRTP displays. Research focused on hardware characteristics such as screen size, number of tactile pins, weight, pin distance, and the mechanism to raise and lower pins. Notably, software UI coverage began to emerge, but contributions remained scattered, leaving many fundamental UI design questions still open [46]. Reviews stressed that 2DRTP technology broadens graphic accessibility but noted that offering dynamic non-visual information alone is insufficient. Effective adoption requires design features that promote user acceptance within the visually impaired community.

Most recently, in 2021, further comprehensive reviews revisited 2DRTP displays and tactile graphic technologies (such as the TPAD [202]) in the context of alternative presentation methods for individuals with BVI [208, 324]. These investigations explored the application domains of both technologies, revealing that over 68% of research focused on educational and daily routine applications, while less than 10% focused on orientation and mobility. The reviews also examined recent advancements in hardware aspects such as pin spacing, surface size, refresh rate, operating voltage, portability, and the challenges of pin mechanism performance. Despite the growing significance of 2DRTP displays as alternatives to static tactile graphics, these systems still face notable challenges, particularly related to cost, durability, portability, and power consumption, which has led to a scarcity of studies in the field.

Overall, all literature reviews contributed to a better understanding of how this technology has evolved. Exploring various studies and analyses has highlighted the groundbreaking nature of 2D refreshable tactile pin displays as an emerging assistive technology. While progress has been made through past research endeavours, the availability of contributions in this field remains scarce and dispersed. The literature reviews have shed light on the advancements in hardware traits and the primary application domains, such as education and daily routine applications, but open design questions persist. Analysis revealed that the development of these devices has advanced more in terms of manufacturing than in user interface design research. Such a pattern is typical in the field of Human-Computer Interaction (HCI), where the focus is often placed on developing the interfaces first, then the research [175]. Nevertheless, a more comprehensive literature review focusing on user interface design contributions is necessary to assess the traits of 2D refreshable tactile pin displays and understand the research gaps.

2.2.3. User Interface Design in 2DRTP Displays

To further advance this technology, it is crucial to establish an updated foundation enclosing all prominent devices and research prototypes. Having conceptualised 2DRTP displays and established their specific requirements, a comprehensive literature was conducted, encompassing the central challenges and obstacles in UI design, as well as the UI aspects that have garnered significant attention throughout the years [237]. We gathered data on 2DRTP displays from both market sources and academic research. The high cost and limited access of some devices, as well as the discontinuation of particular models, pose challenges in interacting with and obtaining hands-on experience with all 2DRTP displays [237, 306]. To address these limitations, we adopted the following analysis methodology.

Methodology for investigating UI design contributions on 2DRTP displays

Information on 2DRTP displays was systematically gathered from reputable scientific sources, including Research Gate, Google Scholar, and similar platforms, using the previously specified nomenclatures for 2DRTP displays (see Section 2.2.1). Employing multiple nomenclatures assured an all-encompassing coverage of different displays, eliminating the risk of unintentionally excluding any noteworthy 2DRTP display from the analysis. Technical product descriptions were also utilised to supplement information on devices lacking scientific contribution. Information from international trade fairs specialising in aids for the visually impaired, such as the SightCity fair and the CSUN assistive technology conference (California State University), was also included. To ensure a rigorous analysis, 2DRTP displays that lacked comprehensive literature reviews or accessible technical reports were excluded from this study.

In total, we included data from 29 2DRTP displays (sourced from both market and academic sources) in the analysis, focusing on selecting the most representative version for devices with multiple versions. For example, the version of the KGS DV-1 display featuring a stylus pen was preferred over the one without it. Some devices did not have distinct versions listed because the differences were either minor or redundant, or one version was simply an extension of another without introducing significant new research. This was the case with the Canute 360 and Graphiti devices. In contrast, versions with substantial changes in software or hardware user interface characteristics were treated as distinct entries, such as the HyperBraille, KGS, Tactis, and BlindPAD project devices. To ensure clarity, most of the collected data and analysis are excluded from this chapter. A more thorough examination, which includes a detailed documentation of each 2DRTP display (organised chronologically and grouped by author/project) with additional information on UI design characteristics (overview tables), is provided in Appendix A.

Table 2.1 provides an overview of all 29 prominent 2DRTP displays from the scientific and market domains. The devices are listed in chronological order (launch year), spanning from 1989 to 2024. The overview details each display's pin count, status (active or discontinued), and associated user interface design research, excluding studies on pin-mechanism technology.

Table 2.1.: Overview of the prominent 2D refreshable tactile pin displays from research and market.

Year	2DRTP-Display	No. Pins	User-Interface Research [α]	Status [β]
1989	DMD 12060	7200	[205, 174, 226, 156, 254, 255, 317, 253]	×
2001	GWP	384	[17]	×
2002	NIST display	3621	—	×
2002	KGS DV-1	768	[109, 315, 313, 314, 170]	×
2003	KGS DV-2	1536	[171, 172, 287, 169, 272, 166, 217]	×
2005	ITACTI	8192	[316, 301, 302]	×
2006	OUV3000	3072	—	×
2008	BrailleDis 9000	7200	[259, 332, 284, 261, 262, 130, 289, 290, 277, 288]	×
2010	Shimada	3072	[270]	×
2012	MobileBrailleDis	960	[330, 334, 335, 333, 184, 185, 187]	×
2014	BrailleDis 7200	7200	[42, 328, 327, 44, 50, 51, 46, 47, 173, 43, 230, 231]	×
2015	Tactis 100	600	—	×
2015	Tactis Table	12000	—	×
2015	Tactis Walk	2400	—	×
2016	Polymer Braille	360	—	×
2016	Graille	7200	—	active
2016	BrailleDis 6240	6240	[48, 49, 203, 265]	active
2016	Hyperflat	3648	[125, 104]	active
2017	BlindPAD-KiT	192	[325, 186, 54]	×
2017	BlindPAD-SMP	768	[32, 30]	×
2018	DotPad	2400	[91, 178]	active
2019	Canute 360	2160	[55]	active
2019	Tactile Pro	2240	[167, 168]	×
2019	Graphiti	2400	[137, 242, 243, 269]	active
2020	Tactile2D	1872	—	active
2021	Braille PAD	1850	—	active
2021	Tacilia	729	[35]	active
2022	Monarch (DTD)	3840	—	active
2024	Tactonom Pro	10472	[240, 241], this dissertation	active

(—): UI Research is not published, or information is unavailable.

[α] Excluding pin-mechanism technology research.
[β] (×): Closed/discontinued (no relevant updates, releases or research over the last three years).

Among the 29 2DRTP displays analysed, only 11 are currently active, either available on the market or supported by ongoing research. Many discontinued devices never progressed beyond the conceptual stage, highlighting the challenges of establishing 2DRTP displays within the BVI community. Despite limited commercial success, these earlier efforts provided valuable insights that paved the way for more advanced devices. Most research focused on improving pin mechanisms for affordability, speed, and durability, while user interface design received comparatively less attention. Nevertheless, 19 displays incorporated some form of user interface design research, reflecting a growing recognition of its importance.

UI Design Analysis

We collected comprehensive data on each 2DRTP display, encompassing hardware user interface characteristics, audio-tactile input and output capabilities, coverage of different user interface domains, and interactive elements designed to facilitate user interaction. This multifaceted approach provides a detailed understanding of the technological and interactive aspects of 2DRTP displays, offering insights into their potential to enhance access to graphical information. A "-" symbol indicates that either the UI feature is absent or that there is insufficient information to confirm its presence. When different values were reported for the same feature, we prioritised the more optimistic value, representing the best available prototype—for example, selecting the higher refresh rate when two different rates were reported.

Hardware characteristics (UI Design)

As part of our user interface definition (see Section 2.1.0.1), we considered both hardware and software UI elements in our analysis of 2DRTP displays. For hardware characteristics, we examined pin count, screen dimensions, pin spacing, portability (weight), refresh rate (speed), and any distinctive or remarkable features of each device (Table A.1).

The most prominent hardware feature of 2DRTP displays is their pin matrix. The displays with the highest number of pins include the Tactis Table (12,000), Tactonom Pro (10,472), ITACTI (8,192), DMD 12060 (7,200), BrailleDis 9000 (7,200), BrailleDis 7200 (7,200), and Graille (7,200). However, pin count does not always correlate with surface size, as not all devices use a 2.5 mm pin spacing (recommended for Braille reading). A notable example is the Graphiti display(4.0 mm pin spacing), which has only one-third the number of pins of the BrailleDis 7200 (2,400 vs. 7,200), yet nearly the same surface area (400 m^2 for Graphiti and 450 m^2 for BrailleDis). Previous studies have shown that a higher pin array density and smaller pin spacing improve shape identification [111]. Larger surfaces are advantageous to enable bi-manual interactions, which are common and natural for BVI users when exploring graphics [270]. However, larger surface areas can make it harder for BVI users to pinpoint tactile elements (see Chapter 4). Proper UI design is essential to overcome these challenges and fully leverage the potential of larger displays.

Another key hardware feature is the refresh rate of the tactile surface. There is a significant disparity in refresh rates across 2DRTP displays, depending on the technology used. Devices in the BrailleDis series are notably fast, achieving refresh rates of up to 20 Hz, while others, such as the Tactonom Pro and Graille, take considerably longer to refresh their screens (0.1 Hz and 0.03 Hz, respectively). To maximize the impact across most 2DRTP displays, UI design must account for varying refresh rates and introduce alternative methods, such as sound, to employ dynamic interactions on slower devices.

Atypical hardware features include the Tactonom's top-facing camera (used for finger detection), the BrailleDis 7200's wide navigation bar, the Graphiti's multi-pin level height, and the multi-line displays of the Canute 360 and Tactis 100 (non-equidistant-pin-distance).

Input and Output

We also assessed the audio-tactile input and output capabilities of 2DRTP displays, which include tactile buttons, support for finger detection and gesture input, multi-touch functionality, and sound output through speakers (Table A.2). Tactile buttons were found to be a reliable and efficient method of interaction, with 22 out of 29 2DRTP displays incorporating them. In contrast, audio support is less prevalent, as only a few 2DRTP displays include integrated speakers. This is primarily because some of these displays are designed to connect to external computers with built-in audio capabilities, as seen in the Tactonom Pro and BrailleDis series. In fact, 22 out of the 29 2DRTP devices are display-only (dependent), but this is changing as newer devices can now function as standalone units (independent). Nevertheless, whether independent or dependent, incorporating custom stereo-position speakers can enhance the reliability of interaction, as it ensures consistent audio output independent of changes in external devices like computer speakers.

Finger detection plays a vital role in 2DRTP displays and tactile graphic readers for enabling tap-based interactions, so much so that even minor inaccuracies can result in user frustration, severely impacting the overall user experience [226]. As a result, the majority of 2DRTP displays support finger detection, either through touch, mounted sensors, or camera-based systems. Some displays go even further, supporting gesture recognition and multi-finger detection, which significantly enhances user interaction [261, 262]. Given its essential role, we developed dynamic audio-tactile user interfaces within this dissertation that rely on accurate finger detection for effective interaction.

Domain coverage

To better understand the domain applications of 2DRTP displays, we categorized them into eight distinct areas: text support, image viewing (graphics), dynamic graph manipulation, orientation and mobility, educational charts, entertainment (games), drawing functionality, and web browsing services (Table A.3). Among these, user interfaces for representing images and graphics (viewers) are the most prevalent, with 23 out of 29 2DRTP displays incorporating them. In contrast, text representation and word-processing interfaces are explored in only 14 out of 29 displays, partly due to Braille text limitations in pin spacing, as previously mentioned. Notably, web browser user interfaces were the least explored domains, with only 3 out of 29 2DRTP displays implementing such functionality.

More dynamic UIs, such as graph manipulation (positioning or moving shape elements within SVG files), drawing interfaces (raising pins where the fingertip rests on the surface), and dynamic games(not all entertainment), were also explored by 2DRTP displays with sufficiently high refresh rates(such as the KGS displays, Dot Pad, and BrailleDis displays). While these domains are noteworthy, our focus was on applications that have been less explored but could provide broader benefits across a wider range of 2DRTP displays without the need for real-time pin refreshment. Such domains include orientation and mobility (primarily representing floor plans and geo-data), explored in 7 out of 29 displays, and educational materials (mainly math learning graphs), present in 8 out of 29.

Interactive UI operations

Lastly, we examined the interactive UI operations explored and supported by 2DRTP displays (Table A.4). Given that the predominant user interface domain in these devices is graphic representation—and manipulation in those with high pin refresh rates—we focused on UI operations serving this purpose. The identified interactive operations were categorised into viewport control (pan/scroll and zoom), element control (read, edit, and highlight), display control (region and filter), and operating system functions (menu implementation).

Panning, zooming, and element reading are the most widely employed graphic accessibility UI operations across 2DRTP displays. Element reading is typically implemented through a tap-to-hear exploration interface, where the user points to an element with their finger, triggering audio information about that element [203]. Element editing and focusing are slightly less explored, as these functionalities have predominantly been implemented in displays with fast refresh rates. Nevertheless, highlighting one element or area using a high pin refreshment rate might not be the only way to help BVI individuals find and pinpoint positions on the tactile surface (see Section 4).

Less commonly used interactive UI operations are region controls (9 out of 29), filter controls (7 out of 29), and menu UI navigation (7 out of 29). Region control is used to split and define specific areas of the screen for different purposes, helping to organise information representation, which proved particularly relevant for arranging elements in distinct parts of the screen in audio-tactile web browsers [255, 254]. Menu navigation UI is less common, possibly because some 2DRTP displays focus on a single application and do not require such functionality. Filter control includes the removal or addition of specific tactile elements or representing information differently, such as inverting raised and lowered dots [88].

Research Insights

Overall, while numerous prototypes and devices have been developed and continue to emerge, the progression of research has yet to catch up, as is often the case in the field of HCI [175]. The research on open-source software and software for 2DRTP devices is still scarce [168]. It is crucial to explore how user interface design can be optimised, ensuring that these innovations are not only viable but also accessible, fostering greater adoption within the BVI community. This analysis provided a comprehensive overview of 2DRTP displays, highlighting potential research paths, from UI elements to implement, domains to explore, and challenges to address. Based on the analysis, we chose to design and implement dynamic audio-tactile user interfaces in the domains of orientation and mobility (see Section 6) and educational materials (see Section 5). Since element editing and focusing have been less explored, we also address dynamic audio-tactile solutions to assist BVI individuals in pinpointing elements or areas on large surfaces (see Section 4).

3. SYSTEM DESIGN

Effective system design is critical for developing functional and user-centred assistive technologies. In the context of dynamic audio-tactile user interfaces, a well-structured design process ensures that hardware and software components seamlessly integrate to provide intuitive and efficient interactions. This chapter describes the systems used to explore dynamic audio-tactile user interfaces for accessing complex graphical information and the UI design methodology applied in their development. Explored audio-tactile user interfaces were implemented on the Tactonom Reader (tactile graphic reader) and the Tactonom Pro (2D refreshable tactile pin display) devices from Inventivio GmbH [116, 117]. While sharing key similarities, these devices also feature critical differences in their interaction flow, which are crucial for understanding how each technology optimises users' engagement with complex graphical data. While not a major scientific innovation, camera-based fingertip detection is essential to the interaction flow of these devices. It is such functionality that enables the dynamic nature of the audio-tactile user interfaces, making them adaptable and responsive to user input. All dynamic audio-tactile user interfaces were designed following a human-centred design (HCD) methodology. Further details on the specific HCD approach employed, including the iterative design cycles, user testing, and feedback integration, are discussed in this chapter, highlighting how each phase of the process contributed to refining the user interfaces to meet the challenges of accessing complex graphical information.

3.1. INTERACTION FLOW

We designed dynamic audio-tactile user interfaces for both tactile graphic readers and 2D refreshable tactile pin displays. The first two research questions (RQ1 and RQ2) were addressed through user interfaces implemented on the Tactonom Reader, while the third research question (RQ3) was addressed by designing UIs on the Tactonom Pro. Despite their differences, both devices share key similarities, allowing us to develop dynamic interfaces adaptable to both, thereby enhancing their broader applicability in assistive technology. One crucial shared feature is camera-based finger detection. While not a novel scientific contribution, this dynamic functionality is fundamental to implementing all user interfaces and is therefore described here in detail due to its significance.

3.1.1. Tactonom Reader

The dynamic audio-tactile user interfaces discussed in Chapters 4 and 5 were implemented and explored on the Tactonom Reader device [117]. The Tactonom Reader is a modern tactile graphic reader (such as the TPad [202], Talking Tactile Tablet [181], or IVEO [112]) that combines tactile information in the form of swell or Braille paper graphics with pinpoint audio explanations. Unlike most tactile graphic readers, the Tactonom Reader does not use a touch-based surface but instead employs RGB camera-based finger recognition for tap-to-hear interaction. The device weighs 5.7 kg and features a metallic magnetic surface measuring 30 cm in length and 43 cm in width (slightly larger than A3 size). Additionally, the device features seven tactile buttons located on the lower part of the surface, including a "back" button, an "execute" button, "left-right" navigation buttons, and three "multi-function" buttons. It is equipped with speakers, though their placement does not support left-right orientation, limiting the ability to create panning effects.

Its functionality is driven by placing tactile graphics onto its surface, which are then scanned by the RGB camera to load associated audio elements for user interaction (Figure 3.1). This process involves utilising a QR code to link the tactile graphic to an SVG file containing shape elements (<*line*>, <*rect*>, <*circle*>, and <*path*>) that represent the tactile and audio fields. After detecting the QR Code, the camera detects four markers on each corner of the graphic to map the SVG hitmap elements to the tactile paper on the metallic surface. Once the four markers are detected, camera-based fingertip interaction becomes available, enabling users to interact with the graphic by pinpointing specific elements with one hand while pressing the "execute" button with the other to access the corresponding audio information (tap-to-hear interaction). More details on fingertip detection are described in subsection 3.1.3.

Figure 3.1.: Interaction flow of Tactonom Reader (version 2.9.9 -2024) [117].

3.1.2. Tactonom Pro

The dynamic audio-tactile user interfaces discussed in Chapter 6 were implemented and tested on the Tactonom Pro device [116]. The Tactonom Pro is a modern, large 2D refreshable tactile pin display (such as the Graphiti [244], Monarch [141], or the BrailleDis 6240 [6]) featuring a total of 10,472 pins arranged in a 119×88 pin matrix (Figure 3.2). Each pin is spaced 2.5 mm apart with a pin diameter of 1.35 mm. Additionally, the device includes 19 tactile buttons—9 on the left side and 10 on the right—comprising one "enter" button, one "select/centre" button, four navigation buttons (left, right, up, down), three "multi-function" buttons, and a "mute audio" button on the right side.

In contrast to other devices in this category, the Tactonom Pro features a top-facing camera (similar to the Tactonom Reader) that allows for fingertip position recognition, enabling tap-to-hear interaction. Unlike the Tactonom Reader, there is no QR Code; instead, four circular markers are detected by the camera to map each pin's position on the RGB frame to a corresponding digital position on the 119×88 pin matrix.

The pin mechanism operates through metal beads placed beneath each pin, which are controlled by a column of magnets that extend across the entire screen. As the column of magnets moves across the screen, it positions each bead directly beneath its corresponding pin or leaves it in place. The screen is then adjusted vertically, causing the pins to either drop (lowered) or remain resting on top of the beads (raised). While this method is cost-effective, it differs from other displays by having a slower refresh rate, with the entire screen taking approximately 10 seconds to refresh. This slower refresh rate, however, encouraged innovative UI design, driving the development of dynamic audio-tactile UIs through continuous fingertip detection with dynamic audio processing. As a result, these UIs can be applied to non-refreshable devices and tactile graphic readers, further broadening the impact of this research.

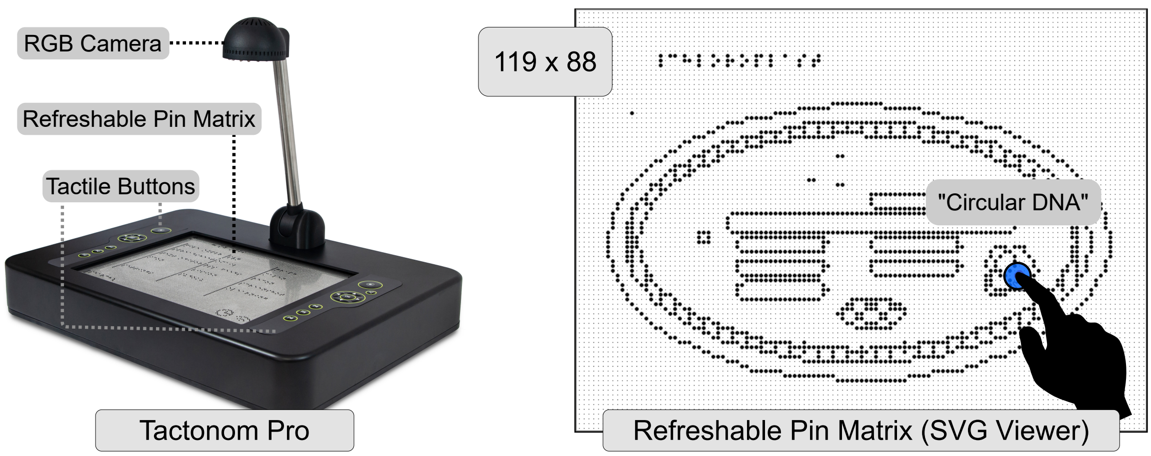

Figure 3.2.: Interaction flow of Tactonom Pro (version 1.5.1 -2025) [116].

3.1.3. Finger Detection

Finger detection is a well-established field of research, with numerous contributions and models already explored, particularly with the rapid growth of deep learning and artificial intelligence technologies. While not a groundbreaking scientific innovation, finger detection is essential to this dissertation, as it enables the dynamic nature of the developed audio-tactile user interfaces. Throughout the evaluation process, it became evident that the functionality of finger detection exceeded initial expectations in importance. If the detection failed, multimodal interaction would not be possible, significantly hindering the overall functionality of the user interface. For the development of more advanced and effective user interfaces, establishing a reliable baseline for finger detection was essential. Furthermore, the relevance of this technology is heightened by the fact that no other 2D refreshable tactile pin displays employ such an approach, and only a limited number of tactile graphic readers utilize it [110], making this research particularly valuable in a largely unexplored context.

The algorithm for camera-based fingertip detection is fundamentally computer vision-based and operates at 15 FPS on both the Tactonom Reader and Tactonom Pro (Figure 3.3). In the first frame, four markers are detected to map the pixels to digital coordinates. Then, each BGR frame's average lightness is calculated using the L channel from the CIELAB colour space. Based on this lightness value, gamma correction is applied to adjust the frame's lightness through a lookup table (LUT). Next, the Red-Green delta difference is used to isolate the hand's colour, highlighting the relevant regions. The result is then thresholded to isolate the hand's region, followed by a morphological operation to refine the detection and filter out noise. The largest cluster of the binary image is selected based on size and its topmost Y position within the digital area, whether it's the paper area in the Tactonom Reader or the pin array in the Tactonom Pro. The topmost Y position of the selected candidate cluster is considered the fingertip position.

This algorithm's main limitation is that it relies on detecting the fingertip at the topmost Y position, which users initially struggled with. When the hand is positioned horizontally, this topmost Y point no longer corresponds to the fingertip but to another part of the hand, such as a knuckle, leading to inaccurate detection. The lack of multi-hand support further limits flexibility. Nevertheless, users adapted over time, and the developed UIs remained effective, benefiting from the pixel-level precision that surpasses other 2D refreshable tactile pin displays.

Figure 3.3.: Algorithm for camera-based fingertip detection applied to the Tactonom Reader and Pro.

3.2. RESEARCH METHODOLOGY

Research methodology varies across disciplines, depending on whether the main goal is to describe and explain the world (empirical research) or to change and improve it (design research) [151]. Empirical research seeks to investigate theoretical concepts through observation and analysis, while design research (or design science) focuses on creating and evaluating artefacts that address real-world challenges. Design science does not only generate new artefacts (Design) but also produces knowledge about their impact (Investigation), requiring researchers to define problem statements, determine user requirements, and evaluate solutions [319]. This methodology is applied to several sciences, including information systems [221], software engineering, and production engineering [180].

In this dissertation, we adopt a **design science approach**. We address our research questions by designing and leveraging dynamic audio-tactile user interfaces, advancing knowledge in the scientific field (knowledge context) while also addressing practical problems of general interest (social context). Inspired by the design science framework defined in [318], Figure 3.4 illustrates the research methodology of this dissertation, highlighting its design science approach and its impact on social and knowledge contexts.

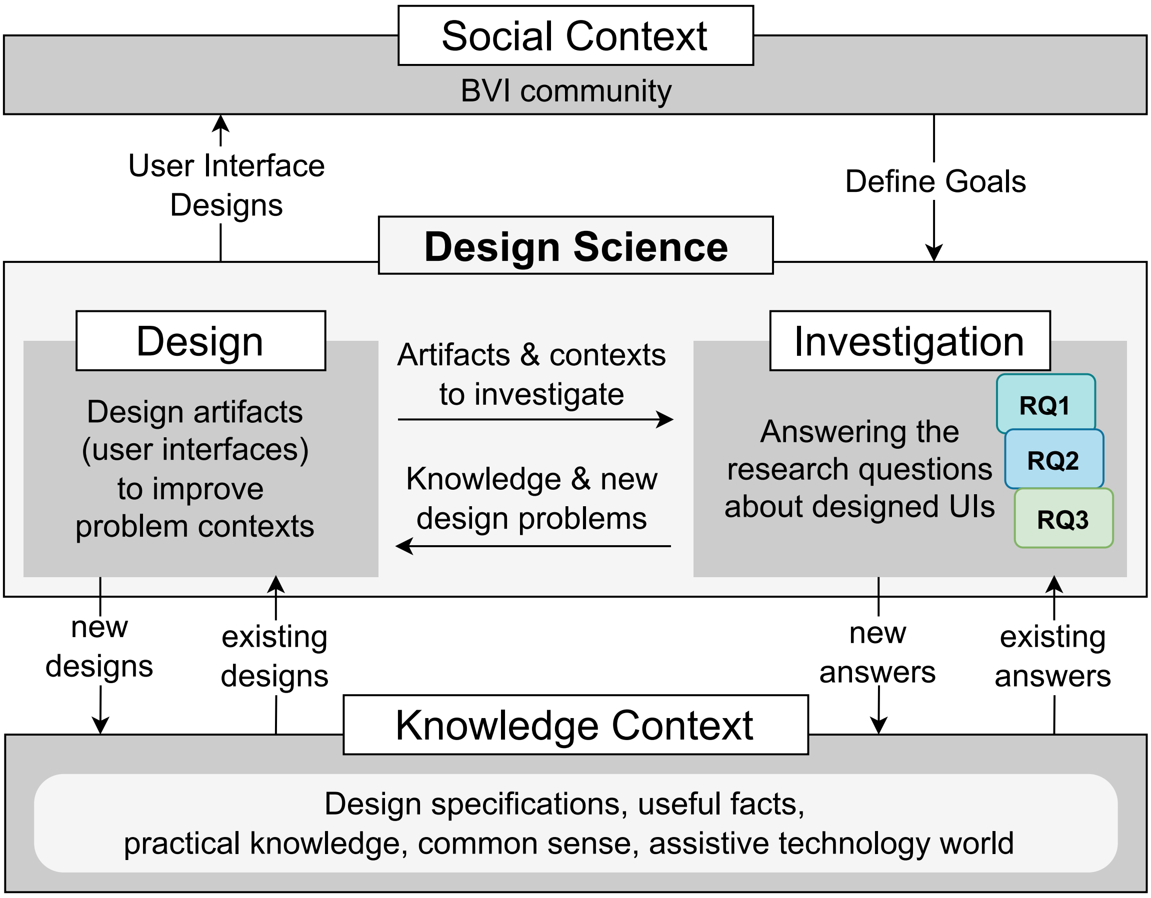

Figure 3.4.: Research Methodology (Design Science Approach) used in this dissertation

3.2.1. UI Design

In addition to the overarching design science methodology, it is necessary to define a UI design methodology for designing dynamic audio-tactile user interfaces.

User interface design is a broad field that offers developers and researchers various approaches to designing user interfaces, including development strategies, user involvement, evaluation metrics, and context domains. Human-centred design (HCD) is one such approach, prioritising user needs, preferences, and challenges by placing them at the core of the design process [212]. According to ISO (International Organization of Standardization), 9241-210 [146], HCD follows an iterative cycle consisting of four key phases: understanding the context of use, defining user requirements, creating design solutions through prototyping, and evaluating these solutions through user testing. An alternative design methodology that complements HCD is participatory design (PD), which sees participants as design partners rather than only sources of feedback during evaluation and requirements gathering [40]. Such an approach emphasises active collaboration between designers and users, allowing users to take on a co-creator role throughout the design phase [193]. PD incorporates several design techniques, including joint idea generation, design workshops, co-design of prototypes, and iterative testing, ensuring that the final design reflects the lived experiences and specific needs of the users involved [252].

Our UI design methodology is rooted in the principles of human-centred design (HCD), where the user's needs, preferences, and challenges are prioritized throughout the design process. To deepen user engagement, we adopt participatory design (PD), extending HCD by involving BVI participants not only as sources of feedback during evaluation and requirements gathering but also as active co-creators during the design (prototyping) phase. Therefore, our methodology involved BVI participants and experts in three stages of the HCD cycle: defining user requirements, prototyping design solutions, and evaluating these solutions through user testing. Figure 3.5 represents the human-centred UI design methodology used in this dissertation to develop dynamic audio-tactile user interfaces.

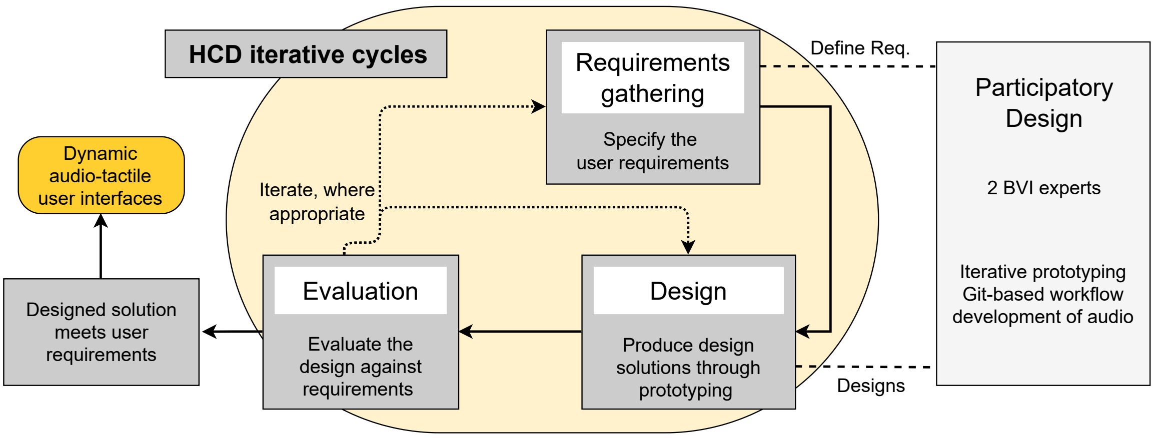

Figure 3.5.: Human-centred user-interface design methodology used in this dissertation. Based on the interdependence of human-centred design activities defined at ISO 9241-210 [146]

For the participatory design process, we involved two BVI experts, one sound engineer, and one software developer, all congenitally blind (visual acuity < 3/60). The process centred on iterative prototyping, where the experts immediately tested small changes to the user interface (UI) to assess whether these met the user requirements. This iterative feedback loop contributed to both the design and requirements-gathering phases of HCD. This included a Git-based workflow where experts independently tested the UIs in various situations and provided feedback through Git issues. This approach facilitated a more efficient, collaborative process, enabling continuous refinement of the UIs without delays on either side. The experts played a significant role in shaping the design, particularly in the development of audio elements. They helped define melodies and tones that would best serve the users' needs, ensuring that the final design was tailored to their preferences and requirements.

We conducted a total of six usability studies, two for each key challenge addressed. In the first usability study for each challenge, we focused on both evaluating user interfaces and gathering user requirements. At this point, the only requirements we had were those collected from the two BVI experts involved in the participatory design phase, as they played an integral role in defining initial design concepts. However, it became apparent that the preferences and abilities of the experts did not fully represent the broader user group. This highlighted the importance of the HCD approach, particularly in conducting further evaluations with a larger group of BVI participants to better capture a wide range of user needs and ensure the final designs were appropriately tailored. Table 3.1 provides an overview of the UI design methods used across various phases of the HCD process, including participatory design and usability studies, alongside the participants involved. Detailed descriptions of each usability study are provided in their respective sections.

Table 3.1.: UI design methods used in this dissertation, with corresponding human-centred design iterative phases and participant involvement.

Section	HCD Phase	Method	Persons involved
4.1.2	Design & Requirements gathering	Participatory Design	2 BVI experts
4.2	Evaluation & Requirements gathering	Usability study	13 BVI users
4.3	Evaluation	Usability study	10 BVI users
5.1.2	Design & Requirements gathering	Participatory Design	2 BVI experts
5.2	Evaluation & Requirements gathering	Preliminary study	4 BVI users
5.3	Evaluation	Usability study	10 BVI users
6.1.2	Design & Requirements gathering	Participatory Design	2 BVI experts
6.2	Evaluation & Requirements gathering	Usability study	9 BVI users
6.3	Evaluation	Usability study	12 BVI users

Part II.

CRAFTING 2D DYNAMIC USER INTERFACES

4. CRAFTING 2D DYNAMIC AUDIO PINPOINT NAVIGATION

Pinpointing elements in graphical information is essential for learning and exploration, yet it remains a significant challenge for individuals with BVI. This is particularly evident when users seek to explore large, detailed tactile graphics using 2D tactile readers or 2D refreshable tactile pin displays. Traditional solutions, such as sighted assistance and Trial-and-Error, are limited and inefficient, while tailored UI solutions seem promising but lack a clear standard for optimal navigation. To tackle this challenge, an Axis-based navigation solution is proposed and evaluated in the context of pinpointing tactile targets in large tactile graphic readers. A user study with 13 BVI participants revealed that Axis navigation falls short in addressing the challenge—eliciting confusion and frustration—while Sonar- and Voice-based solutions yielded superior results. Addressing these challenges, a novel solution—Sonoice navigation—is proposed, merging the strengths of both Sonar and Voice navigation. A second user study with 10 BVI participants revealed that Sonoice navigation outperformed the Sonar, Voice, and standard Trial-and-Error approaches, enabling users to pinpoint elements in large tactile graphics efficiently. Nevertheless, participant preferences for Sonar, Voice, and Sonoice were divided, underscoring the importance of accommodating individual preferences and contextual factors in UI design.

This chapter is based on publications in *Multimodal Technologies and Interaction* (2022, MDPI) [240] and in *Frontiers in Rehabilitation Sciences* (2024, Frontiers) [241].

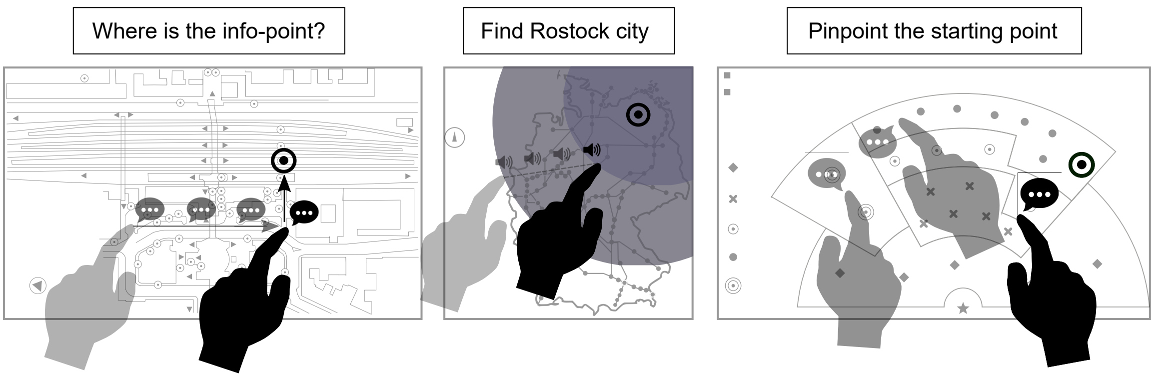

Figure 4.1.: Context applications of **Pinpointing tactile elements in graphical information**

4.1. PINPOINTING ELEMENTS IN 2D TACTILE SURFACES

One key process in learning and exploring complex two-dimensional information is the ability to identify and pinpoint specific elements accurately. This task is essential for understanding and efficiently navigating graphical content. Its relevance and effectiveness arise from finding the starting position of a graphic to engage in focused exploration by locating specific elements or areas in order within the graphic. Beyond that, this task is not restricted to a limited type of graphics but can be used in a broader range of topics, including images, graphs, tables, flow charts, formulas, web pages, maps, and floor plans (figure 4.1).

Yet, the task becomes notably demanding when interacting with user interfaces with large surface sizes. The broader range of possible fingertip positions on these expansive surfaces makes it more challenging for users to explore and pinpoint desired positions and elements precisely [129]. Traditionally, users have relied on the assistance of sighted people who guide their fingertips to the desired positions on the tactile surface. However, this approach diminishes the independence of using the technology autonomously. Without sighted assistance, users often resort to the trial-and-error method of exploring each element individually through tactile textures and audio descriptions. While this strategy fosters user autonomy and free exploration, it becomes difficult to apply in scenarios involving detailed graphics with a large number of elements. In such cases, locating a specific element or detail within the information cluster requires significant time and effort, ceasing efficient information retrieval.

4.1.1. Method-Interface Spectrum

Past literature has explored diverse methods for helping individuals with BVI pinpoint elements on two-dimensional surfaces, including sonification, speech, haptic navigation, and trial-and-error. To understand how individuals with BVI have employed these methods and explore their main advantages and applications, an in-depth literature review was conducted. Given the emerging nature of tactile graphic readers and 2DRTP displays, which have seen limited contributions, the analysis considers a broader range of technologies designed to deliver graphical information to individuals with BVI.

Trial-and-error Navigation

Arguably, the most common practice for individuals with BVI to locate elements on tactile surfaces, including touch screens, tactile graphic readers, and 3D models, involves a trial-and-error strategy. Essentially, users thoroughly explore tactile elements one by one until they find the desired element while building a representation of the graphic content in their heads.

Depending on the assistive technology and device, graphical elements are explored through different feedback. In touch screens, users receive audio speech descriptions [236, 119] or vibration feedback [225] when requesting information on each element. In 2D tactile readers and 3D models, users explore tactile elements individually with touch/speech input by requesting supplementary audio descriptions or reading Braille labels, [202, 59, 110, 56, 112, 181, 123, 124, 81, 83, 311].

In most cases, the trial-and-error approach is employed through the generic tap-to-hear exploration user interface, which, while it helps build a mental picture of the graphical content and supports free exploration, falls short of addressing this task due to its exhaustive nature in locating all elements without additional guidance. People with BVI have pointed out that an assistive UI for pinpointing elements in tactile surfaces is advantageous and critical in this field [119, 240, 241, 201, 83, 82, 311].

Haptic Approaches

Haptic-based user interfaces offer an alternative for assisting BVI individuals in pinpointing elements on tactile surfaces through tactile highlights, wearable tools, or adjustable representations like zooming and panning.

Tactile highlights, such as 3D-printed textural overlays with cutouts, enable users to pinpoint spots on tactile surfaces quickly but are static and require continuous printing and replacement [134]. Movable magnetic tactile markers on an electromagnetic coil array help users pinpoint elements on tactile graphics, but their precision is limited to specific positions on the coil array [285]. Blinking pins have been proven efficient for highlighting positions in 2DRTP displays. [232, 332, 148, 137]. However, its reliance on high refresh rates limits scalability across most 2DRTP displays [237]. Overall, highlight strategies facilitate users in pinpointing positions on 2D surfaces but do not thoroughly guide and navigate the fingertip to the target, which can prove to be a more scalable and more suitable approach.

Hand-wearable haptic interfaces have proven valuable for assisting users in pinpointing positions on 2D surfaces [66, 140, 93, 188], 3D environments [298, 309], and even 2DRTP surfaces [322] (Graille's 10 mm-height slider). However, using such wearable interfaces can negatively impact haptic sensitivity and perception, which are crucial for BVI individuals in learning and exploring tactile graphics.

Another strategy to aid element spotting involves modifying the tactile surface and data representation, which is only possible on dynamic technologies such as 2DRTP displays. The HyperBraille project introduced user interfaces that allowed view changes, zooming, and panning, helping users locate widgets and graphic elements [231, 227, 51, 264, 260]. Nevertheless, adjustable representations, while removing information overload, easing exploration and element pinpointing, also do not thoroughly guide the user's finger to the target position.

Overall, while haptic-based approaches offer clear advantages in assisting people with BVI in pinpointing elements on tactile graphics, they are not scalable solutions, as they depend on interfaces with specific hardware implementations. It may be more promising to explore solutions that can be adapted to a wider range of technologies, such as tactile graphic readers, touchscreens, and 2D pin-matrix displays, thereby having a broader and more impactful influence on the assistive technology landscape.

Sonification Navigation

Sonification-based user interfaces, leveraging sound processing techniques like gain and tone frequency changes, provide an alternative scalable solution for helping users pinpoint elements on 2D surfaces without relying on specific hardware.

Taking inspiration from the conventional car parking aid, pitch-based sonification navigation employs a constant background sound and gradually increases sound frequency as the user approaches the target [98]. This sonar solution resonates with users with BVI, as it is commonly used in assistive technology [219, 128], encompassing tasks like rotating to a specific direction [12, 13], aligning a camera to the correct angle [305], facilitating the learning of line shapes [15], or finding objects through augmented reality headset [127].

Another prevalent sonification-based strategy in assistive technology for individuals with BVI is to establish a background that indicates the user's precise x and y position [149]. While this approach doesn't provide direct guidance to a specific element, it serves to contextualise the user's current position.

Associating a unique sound to each graphic element offers a different but promising strategy (object-to-sound mapping). When the user approaches a specific element, the corresponding audio is played. This method has been shown to be intuitive for on-site object identification [72] and to enhance the proximity perception of tactile elements in touch screens through 3D spatial audio [120]. However, in graphics and situations with numerous details, users may experience information overload due to multiple sounds from diverse sources, potentially making this method less reliable for complex graphics.

Utilising distinct sounds to guide the user using the X and Y axis is another strategy [201]. Following a concept similar to the car parking aid, the frequency of the corresponding sound increases as the user approaches the target's correct X or Y position. While promising, this strategy is not widely adopted in assistive technology and remains relatively untested, requiring further investigation to understand its full potential.

Speech-Only Navigation

Beyond sonification, an alternative audio-driven approach uses speech instructions to thoroughly guide the user's fingertip to a specific position on the tactile surface. Speech-based strategies are primarily categorised into those utilising cardinal directions and those using the clock system.

The cardinal direction speech strategy uses directional instructions such as "top", "bottom", "left", and "right" to guide BVI individuals to specific locations on 2D surfaces. This approach has demonstrated effectiveness in several technological applications, including touch screens, tangible tabletop interfaces, and tactile graphic readers [159, 90, 240, 11, 196], but also in helping point handheld devices in a specific direction [305, 294, 22, 82, 200]. More refined approaches extend beyond directional cues, incorporating proximity feedback through volume adjustment [240] and using subtle modifications in speech instructions, such as suggesting "go a little left" instead of a straightforward "go left" [311], or explicitly stating the distance to target, "5 meters ahead" [106].

Another way to give directional instructions through audio is to use the clock direction system (*3 o'clock, 6 o'clock, 9 o'clock*, and *12 o'clock*). Studies have concluded that BVI people prefer the clock system over cardinal speech instructions when locating elements in tactile floor plans [73]. Others said it is a matter of preference [20, 5], as some users prefer faster and others prefer regular text-to-speech audio speeds [128], some users prefer clock system while others the cardinal direction system. Nevertheless, both clock and cardinal direction systems are standards and strongly present in assistive technology [126].

Research has shown that voice guidance helps BVI people pinpoint and target elements effectively. However, users also revealed discontent with the repetitious and potentially annoying nature of using voice-based navigation [73, 240, 241, 20, 82, 294].

Table 4.1.: Advantages and Drawbacks of Pinpoint Navigation Methods

Method	Advantages	Drawbacks
Trial and Error	Builds a mental picture of Graphical content; Free Exploration;	Exhaustive; Low Efficiency;
Haptic Approach	High Efficiency; Reliable;	not Scalable;
Sonification Approach	High User Satisfaction; Scalable;	Do not convey direct direction;
Speech Approach	High Efficiency; Scalable;	Repetitious; Potentially Annoying;

Table 4.1 summarises the distinctive advantages and drawbacks of each method for assisting users in pinpointing elements in 2D tactile surfaces. Despite the substantial number of different approaches developed thus far, a standardised solution for pinpointing elements in 2D tactile graphic readers has yet to be set. Besides, some approaches presented are inappropriate, such as methods requiring extra hardware or wearable devices, since these are not scalable to other devices. A sound-based approach seems to be the best option for scalable and effective use in this family of assistive technology. Still, research is divided between speech-based and sonification-only approaches. Speech-based approaches generally revealed superior efficiency [73, 240, 241, 20, 82, 294, 305], while sonification approaches were considered beneficial and superior in user satisfaction [87, 13, 113]. Considering these challenges, further exploration is crucial to establish a standardised and scalable solution for efficient element pinpointing in 2D tactile graphic readers.

4.1.2. UI Design: Pinpoint Navigation

This section outlines the design and implementation of all pinpoint navigation strategies assessed in this dissertation, including a standard trial-and-error method and tailored audio-driven user interfaces—Sonar, Voice, Axis, and Sonoice—implemented exclusively on the Tactonom Reader device (Figure 4.2). The tailored interfaces were developed using Java real-time audio processing libraries for volume, pitch, and panning effects, initially with BEADS [204] and later with MINIM version 2.2.2 [85]. Scalability was addressed by designing algorithms within a standardised 100×100 digital coordinate system, enabling consistent audio behaviour by mapping any two-dimensional surface size to this framework.

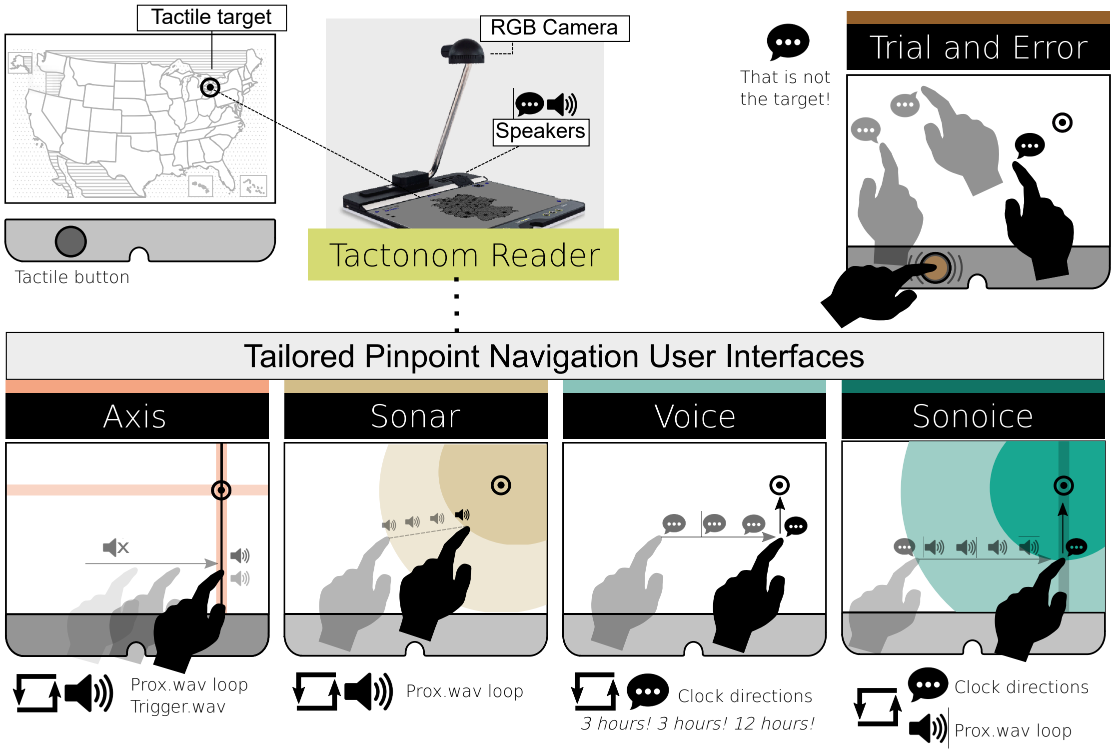

Figure 4.2.: Pinpoint Navigation Strategies: Workflow and key components.

When users lift their hand off the tactile surface of the Tactonom Reader, causing it to move out of the camera's view, the audio feedback is immediately silenced, regardless of the pinpoint navigation strategy currently selected. Upon reaching the target, the system plays a sound to indicate success, "*success.wav*", and all navigation sounds are stopped and turned off. The stereo sound distribution is enabled for all pinpoint strategies, but due to the placement of the Tactonom Reader speakers, the panning effect is not noticeable. The Tactonom Reader does not play any other embedded digital audio information during navigation with any of the tailored user interfaces (Sonar, Voice, Axis or Sonoice). All algorithms operate at a rate of 10 FPS rate, corresponding to the RGB camera's fingertip detection speed, ensuring real-time interaction.

Trial-and-error Navigation

Trial-and-error navigation involves sequentially exploring interactive elements on a surface until the target is located. In the context of the Tactonom Reader device, users can access element information using a combination of hand gestures: one hand presses a button while the other serves as a cursor indicator on a 2D tactile graphic. Each time an element is queried, the device provides audio feedback to convey the associated information, delivered in formats such as text-to-speech or sound. Exploring tactile graphics with a simple button press interface and audio feedback helps to minimise cognitive load and maximise accessibility for individuals with BVI.

Sonar Navigation UI

Drawing inspiration from submarine sound navigation and previous research on pitch-changing proximity navigation, a sonar navigation UI was implemented on the Tactonom Reader (Figure 4.3). A single background beep sound (*sonar.wav*) with a base frequency of 412.150 Hz provides auditory feedback, with both frequency and volume increasing as the user's fingertip approaches the target element. A linear regression function, $y = mx + b$, with $m = -0.0217$ and $b = 2.89$, is used to quantify the magnitude of frequency variation in the beep sound. In this equation, x represents the distance between the user's fingertip and the target element in the 100 x 100 digital space. Y denotes the frequency increase relative to the baseline of 412.150 Hz, with the beep's frequency rising as the user approaches the target element. When the user's fingertip is precisely at the target ($x = 0$), the frequency increase reaches its maximum value of 2.89, resulting in a frequency of 1191 Hz (2.89×412.150 Hz). The background beep sound has a duration of 0.22 s and loops while Sonar navigation is active. All the duration and frequency value adjustments were fine-tuned during human-centred design testing with BVI individuals at Inventivio GmbH.

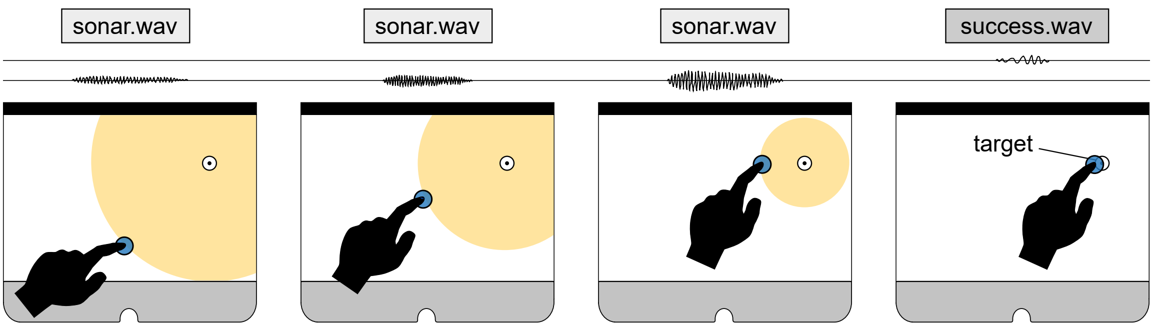

Figure 4.3.: Sonar Navigation UI Workflow

Voice Navigation UI

Building on prior literature, two voice navigation user interfaces were implemented in the Tactonom Reader: clock-based and cardinal-direction voice navigation (Figure 4.4). The cardinal-direction voice navigation was the first designed, providing speech-based instructions indicating the direction of the target relative to the user's fingertip position. Four distinct audio instructions—"go up", "go down", "go left", and "go right"—are used to guide the user, with only one voice command played at a time. These instructions are generated using text-to-speech synthesis, ensuring straightforward language scalability. The specific voice command is determined based on the biggest distance between the user's fingertip and the target element. This ensures the voice feedback is consistent and reliable feedback regardless of the user's starting position on the tactile surface. The volume of the voice commands is negatively proportional to the distance from the fingertip to the target.

Based on the conclusions drawn in Section 4.2, the implemented voice navigation was refined, transitioning from the cardinal-direction system to a clock-based navigation system [240]. This change was necessary because the *top* and *bottom* voice cues introduced ambiguity, confusing users regarding whether these directions should be interpreted in a 2D or 3D context. The revised clock-based voice navigation replaced directional speech cues with clock positions: "3 o'clock," "6 o'clock," "9 o'clock," and "12 o'clock". The Minim library was additionally utilised for both volume adjustment and stereo panning as the user approaches the target element. While some navigation systems employ additional clock directions such as "2 o'clock" or "5 o'clock" [38], these were deliberately excluded to favour simplicity and familiarity, aligning the UI more closely with the majority of the clock-speech guidance systems used in tactile graphics navigation [126, 5, 20, 73]. While additional directions can provide finer precision, they also introduce increased processing time and still necessitate micro-adjustments.

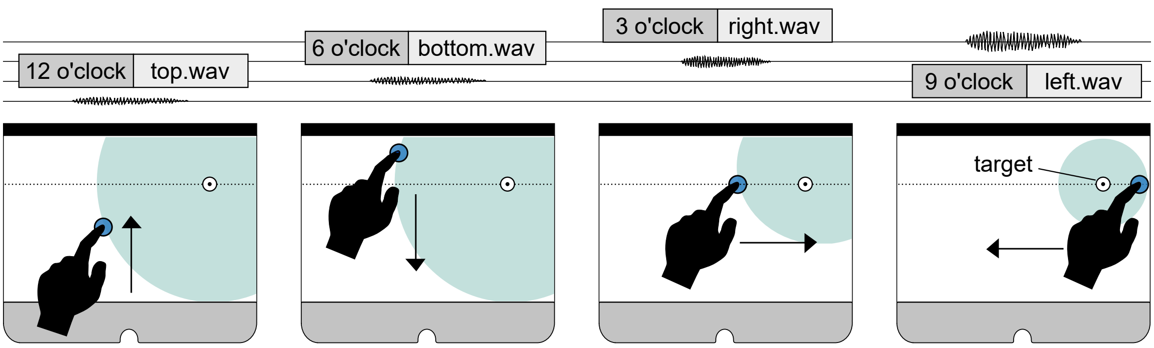

Figure 4.4.: Voice Navigation UI Workflow - left-positioned grey voice commands correspond to the clock-based version, while right-positioned white commands correspond to the cardinal-direction version.

Axis Navigation UI

Building on prior research on X and Y axis positioning for user navigation [201] and initial insights from BVI workers at Inventivio GmbH, this dissertation introduces a new axis-based navigation UI (Figure 4.5). In this UI, no constant background sound is played at the start. Instead, audio feedback is triggered when the user's fingertip reaches the target's X or Y coordinate on the tactile surface. Once the fingertip is aligned with either the X or Y axis of the target, a single 'trigger' beep sound is played, indicating that the user is on the correct axis. After the 'trigger' sound, a brief background sound (lasting 0.4 seconds) begins to play in a loop. As the user moves along the axis toward the target, the background sound becomes louder and higher in pitch, with the volume and pitch changes being inversely proportional to the distance from the target. If the user moves away from the target, the sound's volume and pitch decrease accordingly, and an 'error' sound (0.4 seconds) additionally plays to provide explicit feedback that the movement is incorrect. If the fingertip moves off the axis entirely, the background sound is silenced. To help users maintain their position on the axis, a 1 cm threshold for minor deviations from the target axis was set, meaning small misalignments won't trigger sound changes.

The primary goal of this approach was to minimize auditory clutter and annoyance while maintaining an efficient and user-friendly interaction. Initially, the user moves their fingertip vertically along the axis (from bottom to top) until the trigger sound is played, indicating that they are aligned with the target's Y coordinate. Once the trigger sound is heard, the user can then navigate horizontally (left or right) to reach the target. Alternatively, the navigation process can begin by moving the fingertip horizontally from left to right, followed by vertical navigation. This dual-direction approach aimed to offer flexibility, allowing the user to start from either axis based on their preference or context.

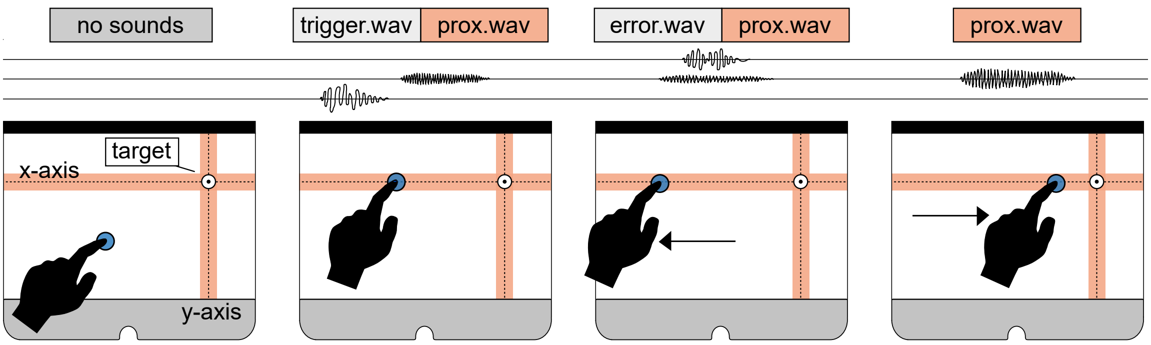

Figure 4.5.: Axis Navigation UI Workflow: Audio feedback is only triggered when the fingertip crosses the x or y-axis threshold, with no feedback provided when the fingertip is within the white areas

Sonoice Navigation UI

Following a human-centred design approach to enhance pinpoint navigation and drawing on the outcomes of the investigation raised in section 4.2, this dissertation proposes a novel strategy called **Sonoice** (sonar + voice). This strategy aims to combine the advantages of sonar proximity feedback and voice-guided directional pinpointing, offering a comprehensive and innovative solution for tactile surface navigation (Figure 4.6).

Sonoice begins with a single voice direction instruction using the clock system, followed by a looping proximity beep. This initial voice direction corresponds to the axis with the largest distance to the target: either vertically (12 or 6 o'clock) or horizontally (3 or 9 o'clock). As the user's fingertip approaches the target, the volume and frequency of the proximity beep sound dynamically adjust following the same linear regression function employed in the Sonar navigation strategy. This continues until the user reaches the target element's x or y threshold based on the voice instruction. For the direction voices "3 o'clock" and "9 o'clock", this threshold is the x position, while for the voices "6 o'clock" and "12 o'clock", it is the y position. Once the user crosses the threshold, a trigger sound plays and a new voice instruction is given, guiding the user towards the target. The background beep then resumes, guiding the user along the next axis until the next threshold is reached. By continuously giving new voice instructions at each x or y threshold of the target element, the method ensures that the user is always directed towards the target, allowing users to move diagonally and still pinpoint the target.

The Sonoice UI incorporates a wrong-direction feedback mechanism to assist with directional accuracy. If the user deviates from the intended path, the system replays the last voice instruction to help correct the trajectory, prioritising positive reinforcement over negative cues, such as error tones or alerts. Additionally, if the user stays still for more than five seconds, a new voice instruction is triggered based on the greater distance to the target element. To avoid repetitive voice commands, the system delays the following voice command for 5 seconds after the previous one, with the exception of when the user reaches a new x or y threshold.

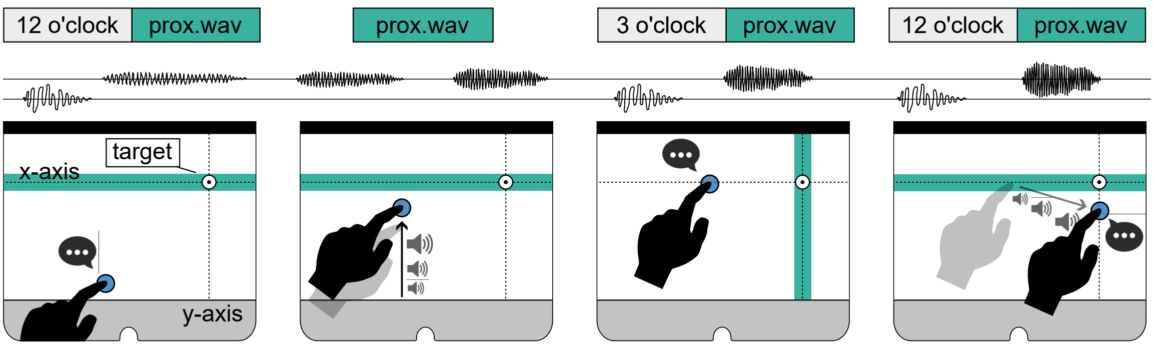

Figure 4.6.: Sonoice Navigation UI Workflow: Supports imprecise and diagonal movements

4.2. NAVIGATION THROUGH STRAIGHT DIRECTIONS

Given the lack of a clear standard or superior solution for assisting BVI individuals in pinpointing elements on large surfaces, an initial user study was conducted to evaluate and validate the performance of axis-based navigation in comparison to existing voice-based and sonar-based solutions. Such user interfaces were implemented in the Tactonom Reader device and tested on A3-size SVG-based tactile graphics. The aim was to assess whether the new axis-based navigation outperformed state-of-the-art solutions in terms of efficiency and satisfaction while gathering valuable feedback on the strengths and weaknesses of each solution.

Participants

Thirteen BVI participants (six females, seven males; Table 4.2) took part in the study, recruited from Osnabrück through the local blind association (BVN). Interested individuals received study details and participated if they reported a medical diagnosis of visual impairment or blindness, as visual acuity was not directly measured. Exclusion criteria included being under 18, substance abuse and medical conditions affecting cognition, hearing, communication, touch, or motor skills. The University of Osnabrück ethics committee approved the study, and all participants provided informed consent. Self-reports categorised participants into three groups: two as congenitally blind (CB), eight as late blind (LB), and three as visually impaired (VI). Additionally, participants' experiences with tactile graphics and 2D user interfaces (tactile graphic readers or 2D refreshable tactile pin displays) were collected.

Table 4.2.: Participant demographics and experience with graphics and 2D user interfaces (P1-P13).

Users	Gender	VI Type (VA)	Tactile Graphics Experience	2D UI Experience
P1	male	LB (< 3/60)	no	no
P2	male	VI (< 6/60)	no	no
P3	female	LB (< 3/60)	city maps	no
P4	male	LB (< 3/60)	no	no
P5	female	LB (< 3/60)	no	no
P6	female	LB (< 3/60)	city maps	no
P7	male	VI (< 6/60)	tactile paintings in museums	no
P8	male	CB (< 3/60)	yes	BrailleDis 6240 [6]
P9	female	CB (< 3/60)	floorplans and maps	Tactonom Reader
P10	male	VI (< 6/60)	no	no
P11	female	LB (< 3/60)	no	no
P12	female	LB (< 3/60)	calendars	no
P13	male	LB (< 3/60)	city maps	no

Visual acuity (VA) levels defined by the WHO [3].

Materials - Graphics

A total of ten audio-tactile SVG-based graphics were used: three for contextualization, one (a tutorial) for learning pinpoint strategies, and six for UI evaluation (Figure 4.7).

The contextualization graphics were sourced from the open-source ProBlind database [233], including a state-distributed German map, a solar system diagram, and a train station floor plan. These diverse graphics were chosen to represent various contexts, helping users understand the Tactonom Reader's concept and workflow.

Explicitly created for this study, the tutorial and evaluation graphics were designed using Inkscape (SVG format) with the ProBlind layout, incorporating a QR code in the top-right corner and four blue circle markers at the corners. The final SVG files were uploaded to the ProBlind database, printed on swell paper, and processed through the PIAF (Tactile Image Maker) heating chamber [223]. The tutorial graphic features four tactile targets (10 mm diameter circles) connected by straight lines to a central starting point, serving as clear guidelines for explaining the navigation UIs. Evaluation graphics are grouped into three pairs based on their structural patterns. Graphics 1–2 include the same tactile targets and additional circles arranged in uniform patterns. Graphics 3–4 depict simplified train station layouts with the same tactile targets, designed to assess whether adding extra tactile elements impacts navigation. Train station representations were selected due to their relevance in mobility and orientation for the BVI community [209]. Graphics 5–6 consist of clusters of tactile points distributed across the graphic surface, with Graphic 5 featuring points in straight lines and Graphic 6 with points haphazardly arranged. In these graphics, targets are purely digital (blank areas, not tactile), reflecting scenarios where targets represent blank areas instead of points; this information was concealed from users. Graphics 5–6 were designed to evaluate the UIs based solely on audio feedback.

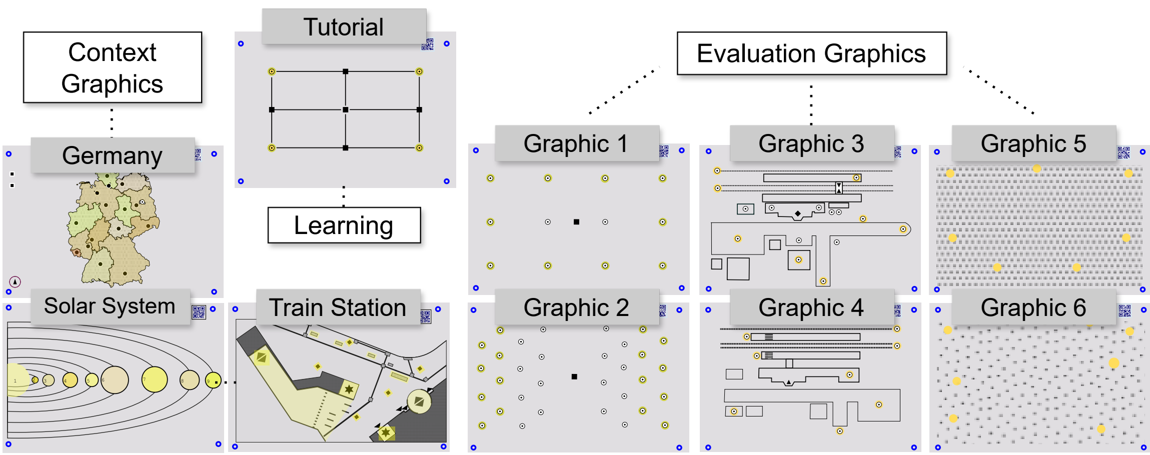

Figure 4.7.: Audio-Tactile graphics used in the study. Yellow elements represent the digitally labelled audio targets, and black information represents the tactile information that participants could perceive. Blue markers are not tactile sensitive and are only used for mapping the tactile graphic to its digital format. The blue title texts were enlarged for viewing purposes.

4.2.1. Experimental Setup

To ensure that each participant experienced all three navigation user interfaces (voice, sonar, and axis), this study employed a within-subjects design. A counterbalancing strategy systematically varied the sequence of UI interactions to control for order effects. With three interfaces, six unique order combinations were assigned to the 13 participants, ensuring that each sequence was tested twice, except for one, which was tested three times due to the odd number of participants. Additionally, the order of evaluation graphics was randomised to prevent sequence-related biases. Each session lasted 90 minutes and was conducted individually. Figure 4.8 illustrates the step-by-step progression of the experimental procedure, illustrating its specific phases for clarity and comprehension.

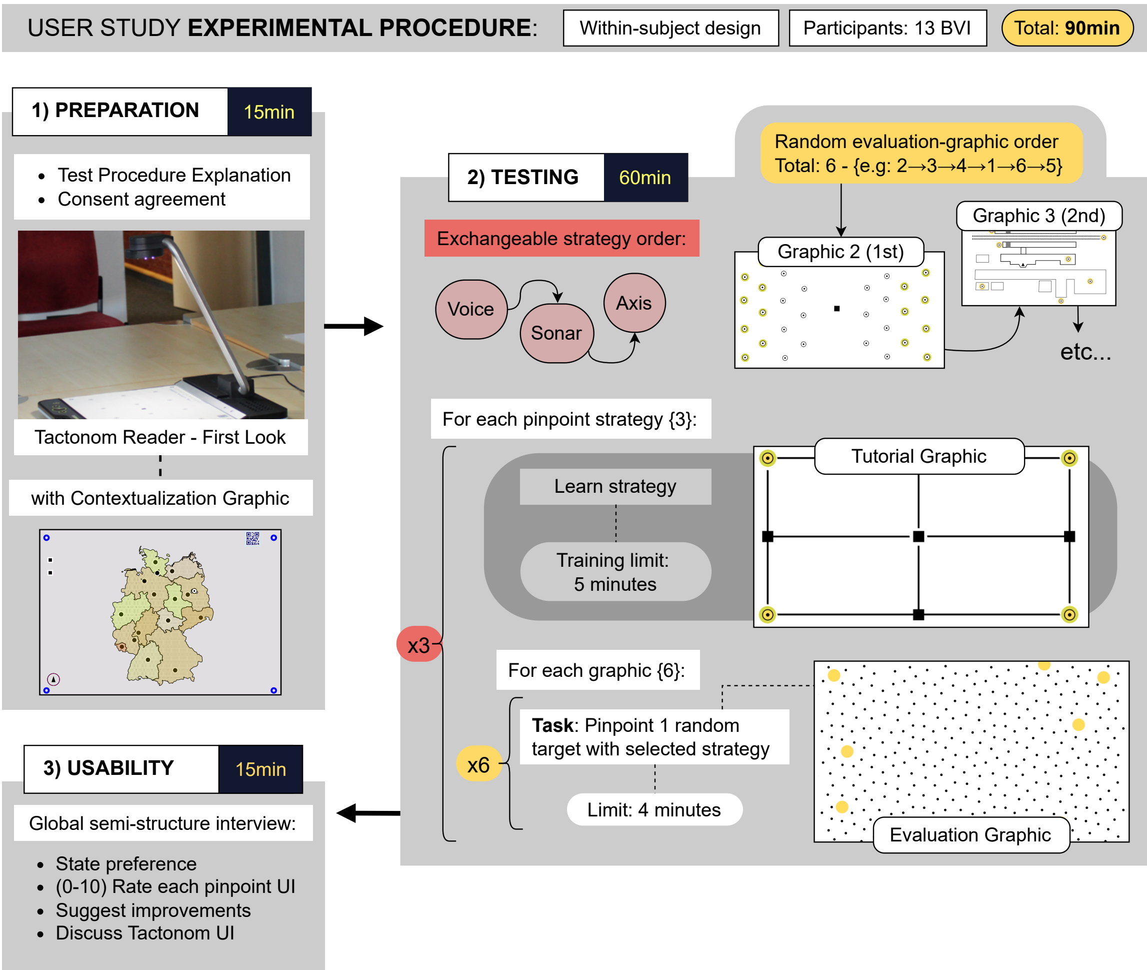

Figure 4.8.: Experimental Procedure: Navigating through Straight Directions

Study Procedure - Preparation

At the beginning of the study, participants were informed about the purpose and procedures. Consent was obtained through either a signed form or verbal agreement, which was audio recorded. Participants were also reminded of their right to withdraw from the study at any time without explanation. Following this, participants spent about 15 minutes becoming familiar with the Tactonom Reader device (see Section 3.1.1), including its dimensions, camera-based finger detection, tactile UI buttons, and graphic reloading workflow. During this time, participants were free to load the contextualization graphics of their choice and interact with the technology to evaluate its benefits and scalability potential. The session duration was insufficient to explore additional functions of the Tactonom Reader.

Study Procedure - Testing

After familiarisation with the Tactonom Reader, the order of the pinpoint navigation strategies and evaluation graphics was assigned. A tutorial graphic was placed on the device, allowing participants to learn the first assigned navigation UI within a five-minute window. Once the navigation UI was understood, each evaluation graphic was set on the device. Participants were instructed to place their index finger on the device surface and locate one randomly selected target for all six graphics. The limit for pinpointing each target was 4 minutes. After successfully locating all six targets across the six evaluation graphics, the procedure was repeated with the remaining two navigation UIs, each with a different random order of evaluation graphics and new randomly selected targets, to prevent participants from memorising target locations.

Study Procedure - Usability

The final phase of the experiment involved a semi-structured interview to evaluate the usability of the Tactonom Reader and assess the efficiency of the navigation UIs in assisting pinpoint navigation for BVI users within tactile graphics. During this, participants rated the usability of each navigation UI on a scale from 0 (poor) to 10 (excellent). The interview also sought to identify areas for improvement in both the device and the implemented pinpoint navigation UIs. Further details on the task can be found in the supplementary material (see Appendix B.1).

Data Analysis Methodology

A mixed-methods approach was employed, integrating both quantitative and qualitative data, including semi-structured interviews. Analyses focused on navigation UI efficiency (trial duration, move counts) and user satisfaction (average user score and user comments). Descriptive statistics, including averages and standard deviations, were used to summarise the quantitative data. Subjective data from interviews were analysed using thematic analysis. Statistical tests were not conducted.

4.2.2. Results

The primary focus of the analysis was comparing the three pinpoint navigation user interfaces (section 4.2.2.1). Additionally, further investigations were conducted to examine differences across tactile graphics (section 4.2.2.2) and variations in user strategies for locating and pinpointing elements (section 4.2.2.3). In data figures, boxplots exhibit medians as solid lines, with outliers shown as grey diamonds for clarity.

Pinpoint Navigation UI Comparison

Trial duration (total time taken by the user to locate a target) was analysed as a measure of efficiency across the pinpoint navigation UIs (sonar, axis, and voice), with shorter durations indicating higher efficiency (figure 4.9 - left plot). The mean trial duration was 40.2 ± 31.0 seconds for the sonar-based method, 47.0 ± 39.6 seconds for axis-based navigation, and 23.3 ± 11.1 seconds for voice-based navigation, which had the shortest mean duration. The two longest trials, lasting 235.6 and 226.4 seconds with the axis and sonar UIs, were excluded from figure 4.9 for clarity. Excluding these two outliers, the shortest trial was 4.6 seconds and the longest 150.2 seconds.

To gain further insight, the distribution of trial durations was also examined as a function of the distance between the participant's initial fingertip position and the target position. This comparison controls for the bias introduced by the starting position by accounting for cases where users begin closer to the target, making the task easier compared to starting farther away. A scatter plot was created to differentiate the three navigation UIs, as shown in figure 4.9 - right plot. A regression line was fitted for each UI scatter plot distribution. The sonar navigation's regression line has the smallest slope, suggesting a slower increase in time as the distance to the target increases compared to the other navigation UIs. Despite this, voice-based navigation UI still emerged as the most efficient method for pinpointing elements in tactile graphics when the start-target distance was considered. These results provide evidence of the potential high performance of the voice-based navigation UI.

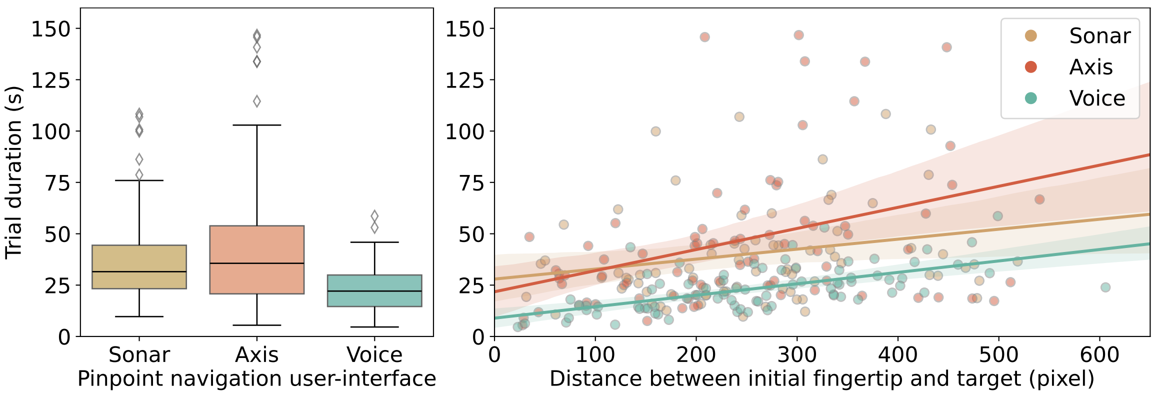

Figure 4.9.: Efficiency analysis. Left: Trial duration distribution (s) per navigation UI. Right: Trial duration as a function of the start-to-target distance. (pixels).

Efficiency was also assessed by counting the "moves" participants made before reaching the target, based on x-y fingertip detections collected by the camera (figure 4.10 - left plot). The axis-based method had the highest mean number of movements, with 784 ± 687, followed by the sonar-based method, with 734 ± 553, and the voice-based method, with the lowest mean of 358 ± 162 movements per participant. The maximum number of moves per trial was 4306 during sonar navigation, while the minimum number of moves was only 59 while using voice navigation. In agreement with the prior results, voice navigation indicates higher performance than the other approaches. During the interaction, slower reaction times were observed when interacting with the axis navigation UI.

Regarding user satisfaction, during semi-structured interviews, participants were asked to rate each navigation UI on a scale from 1 (not useful) to 10 (perfect). The voice-based UI received the highest average rating of 8.0 ± 1.31 (median = 8.0), followed by the sonar-based UI with a mean of 7.62 ± 1.61 (median = 8.0). The axis UI had the lowest average score, with 5.85 ± 2.30 (median = 6.0). The distribution of user ratings is shown in figure 4.10 - right plot. These results roughly align with the trial duration analysis, highlighting the superior performance of the voice-based UI. However, it also shows that the user rating for the sonar navigation UI was only marginally lower than that of the voice solution.

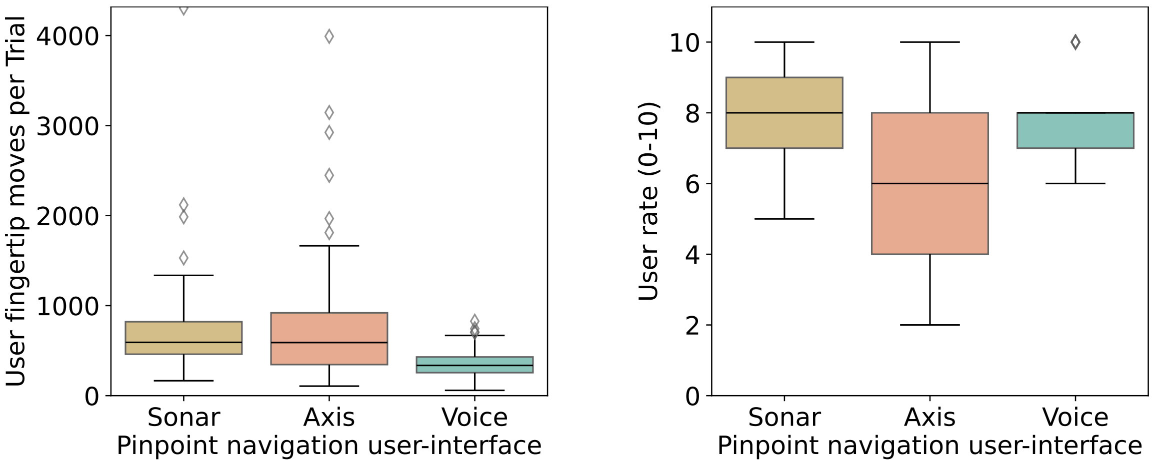

Figure 4.10.: Move counts and user ratings analysis. Left: User fingertip movements per trial across the navigation UIs. Right: User's rating (0-10) across the navigation UIs.

Qualitative feedback was also gathered from participants during the semi-structured interviews. Users commented on the difficulty of using the axis navigation, which requires straight directional movements and lacks feedback when the finger is not on an axis: "If you don't move your finger in a straight direction, you are out!", "If the device is not playing any sound, we do not know if it is actually doing something or not.", "The tone should be constant. Otherwise, it might cause uncertainty whether the device (or myself) is functioning correctly." Ten out of the 13 participants were unable to navigate in a straight line, leading their fingertips out of the axis area and silencing all audio cues, which led to confusion: "When you found the signal, and it disappears again, this is causing uncertainty.", "Sounds were very good, but deviating from the axis was annoying."

On the other hand, the voice-based method received positive feedback for its simplicity and ease of learning, "It requires the least cognitive effort," "You get there faster because he gives the most direct instructions without delay and interpretation!" Some participants preferred the sonar-based method for its more pleasant sounds, while the voice instructions were considered less pleasant and repetitive, "Sonar was a nicer sound! It's nicer to listen to than the 'go up!' instruction.", "Was not the fastest, but it didn't annoy me!". Participants also noted that preferences depend on context and assistive technology, "Who is more into sounds will prefer the sonar UI and who does not, the voice UI." Regarding the sonar-based UI, participants commented on its ability to move diagonally, "It is also possible to navigate diagonally; the audio instructions are very direct and do not overlap.", "It is more fun, as it is intuitive to use through the sound and allows for all kinds of movement." Overall, participants gave positive feedback on both the sonar-based and voice-based UIs, while the axis UI received more negative comments.

Tactile Graphics Comparison

To assess the impact of tactile graphic design on navigation UI performance, trial durations and user movement counts were compared across the six different evaluation graphics (figure 4.11). Graphic 5 (cluster of points uniformly arranged) had the shortest average trial duration at 31.3 ± 22.2 seconds, while Graphic 6 (cluster of points haphazardly arranged) had the most extended average trial duration at 51.7 ± 48.5 seconds. Notably, the two most divergent most extended trial durations were observed in Graphic 6 (not shown for clarity), though all graphics exhibited outliers. When comparing movement counts per trial, Graphic 6 had the highest average of 907 ± 890 movements, with a maximum of 4306 movements (outliers excluded). Graphic 5 had the lowest average of movements (502 ± 311), consistent with its faster trial duration. During evaluation, participants had the impression that the points in Graphic 6 were uniformly arranged despite the uneven spacing. Participants showed signals of confusion but were still able to pinpoint the targets. Overall, efficiency disparities were minimal, supporting the idea that navigation UIs can help BVI individuals pinpoint elements independently of the tactile graphic design.

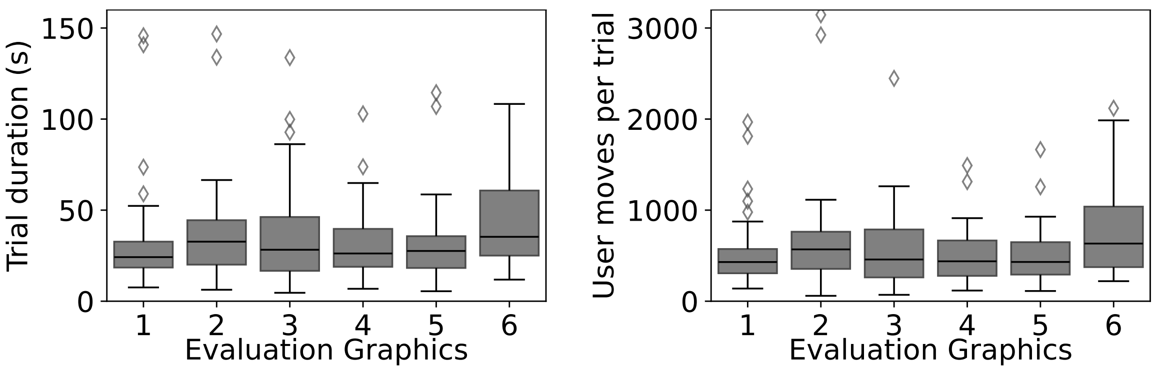

Figure 4.11.: Graphics design comparison. Left: Trial duration distribution (s) per evaluation graphic. Right: User fingertip movements per trial across the evaluation graphics.

Strategies for Pinpointing Elements in Tactile Graphics

Apart from measuring trial duration, fingertip starting positions were analysed throughout each trial to identify possible user strategies when interacting with the navigation user interfaces (figure 4.12). The distribution of initial fingertip positions on the Tactonom Reader's two-dimensional surface (x and y coordinates) reveals a clear tendency: most starting positions cluster at the centre and bottom centre of the device. This pattern remains consistent regardless of the navigation UI. Fingertip positions were further examined in relation to the six evaluation graphics, confirming that initial placement does not significantly vary with the graphic type. Surprisingly, no systematic adaptation can be seen in the course of the experiment, and the participants use a relatively constant starting position.

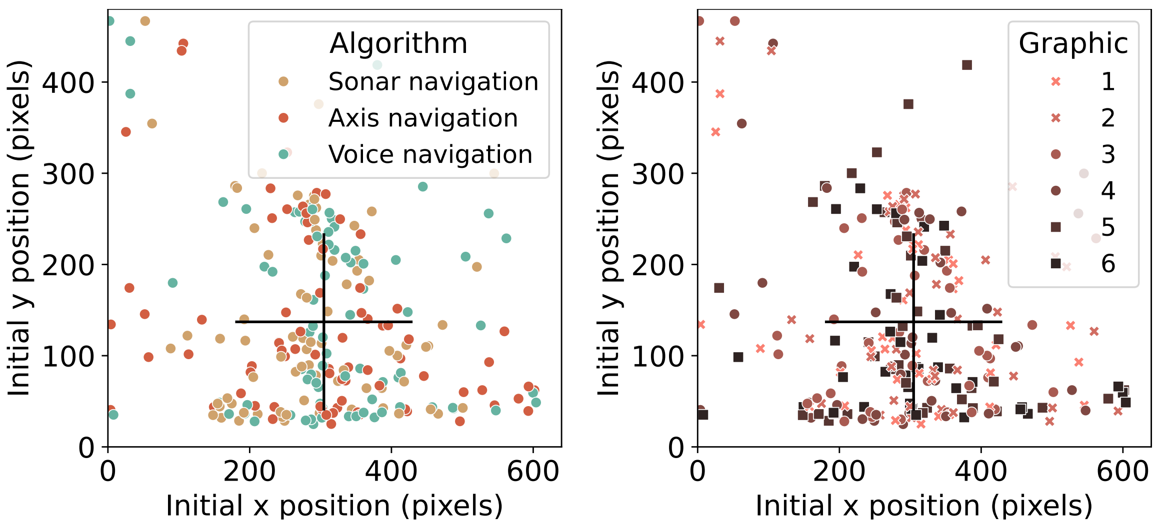

Figure 4.12.: User strategies analysis: comparing initial fingertip position in the x-y pixel coordinate plan of the Tactonom Reader display (640x480). The left plot correlates the x-y position with the type of navigation user interface, and the right plot correlates with the evaluation graphic used. The black cross represents the centre of gravity (mean initial fingertip position).

4.2.3. Discussion

Investigating navigation user interfaces to assist BVI individuals in pinpointing targets within tactile graphics has yielded valuable insights. Participants demonstrated interest and found utility in using the implemented pinpoint navigation UIs: “I would like to use them!”, “Yes, they are totally useful for finding the target and can also be applied to various practical examples.”, “Yes, both sonar and voice are very capable of this!”. To address the research gap and develop a better solution for this key challenge, it is crucial to discuss the limitations of the proposed axis navigation and the trade-offs between user preferences and UI performance. Additionally, the discussion addresses the minor performance differences across the evaluation graphics, offering insights into their causes and implications.

The study results indicate that the voice-based navigation user interface was, on average, the fastest, most intuitive, and most preferred by participants. This is supported by existing literature on speech vs tone-based navigation UIs [82, 294, 305], but the causes for its higher efficiency are not immediately evident. Only when analysing all strategies does it become clear why voice-based navigation performs better.

Moving Fingertip in a Straight Direction

While promising, the proposed axis-based navigation had a low average user rating of 5.85 and was associated with slower reaction times. This can likely be attributed to the increased time and cognitive load required to interpret the axis audio signals. However, the argument that fewer sounds lead to better performance does not explain why the voice-based method, which uses four sounds, outperformed the sonar-based method, which uses only one. Insights from participants' responses in the semi-structured interviews and observations during interactions revealed key difficulties with axis-based navigation.

Blind and visually impaired people have difficulty moving their hands and fingertips in a straight line. This was especially evident on the large surface of the Tactonom Reader, where movement deviations are more visually pronounced but more haptically challenging. The axis method is based on the x and y-axis, which implies that the user should navigate in a straight vertical or horizontal line to the target. If the user leaves this line at any point, audio feedback stops. It was observed during interactions that participants would typically not follow this line in a straight direction but in a slightly diagonal direction. This diagonal direction would lead their fingertips out of the threshold borders of the x-y axis of the target, therefore silencing the audio cues. The participants did not understand why the sound had stopped since they followed and maintained a straight direction in their mental image, generating frustration and prolonging the navigation task.

The Balance between Performance and User Preferences

When considering trial durations, voice navigation is clearly the best approach. The average trial duration for sonar navigation was closer to that of axis navigation than to voice navigation. Moreover, on average, participants made nearly half of the movements when using the voice-based method compared to the other methods. Participants supported these results by reporting during the semi-structured interviews that they preferred the voice-based method instructions as being more direct, "You get there faster because he gives the most direct instructions without delay and interpretation!". Further explanation involves user contexts, where Voice-to-text interpretation is a task humans are often familiar with, making this UI more intuitive to interpret than the other alternatives.

Examining the average user ratings revealed a different trend compared to the trial duration results. Notably, the voice and sonar methods, which had distinct efficiency outcomes, delivered similar satisfaction among users, even though axis navigation did not. The closeness in user ratings between voice and sonar can be attributed to the heavy influence of different user experiences and preferences: "Who is more into sounds will prefer the sonar UI and who does not, the voice UI.". Although the voice method provided the quickest navigation, it was also repetitive, which some participants found annoying, affecting their overall satisfaction. Moreover, the sonar method's unique ability to support diagonal movements was seen as a positive feature, making it more favourable for certain users despite its slower speed: "(Was not the fastest, but it didn't annoy me! (Sonar)".

Tactile Graphics Distinctions

Evaluation graphics were divided into three groups according to their characteristics during the tests. When looking at trial efficiency, Graphic 6 stands out for its higher average duration time and higher average number of movements per trial. The two most divergent outlier trials were sampled with Graphic 6. Together with Graphic 5, these were the only evaluation graphics containing digital-only (not tactile) targets, where users could only rely on audio feedback to find them. Moreover, the fact that the tactile information is irregularly dispersed in the tactile paper can mislead the user's direction, especially in the axis-based and voice-based methods, where users follow straight directions. It was observed during interactions that users would use the points with the intent of moving in vertical or horizontal line directions, when the irregular points would lead them to diagonal directions instead. No participant could figure out that the tactile points of Graphic 6 were not dispersed in vertical and horizontal straight directions. Although Graphic 5 also contains blank space targets, its points are uniformly dispersed in straight vertical and horizontal lines, allowing participants to use these as guidelines to move in the direction of the target location, as observed during sessions. This is an intriguing insight since it shows us that tactile graphics design still plays a vital role in perceiving and finding information.

4.3. SONOICE: COMBINING SONIFICATION WITH VOICE

Building on the results of the first study presented in 4.2 and following the human-centred design methodology adopted in this dissertation, a second user study was conducted to evaluate the capabilities of the Sonoice navigation UI for pinpointing elements on larger surfaces. Beyond comparing the Sonoice UI with the established state-of-the-art sonar and voice solutions, this analysis expands the comparison to include the trial-and-error approach, assessing the performance of all four strategies across efficiency and user satisfaction on the Tactonom Reader device. The inclusion of the trial-and-error approach was intended to investigate whether a structured user interface is essential, as relying solely on trial-and-error may not adequately address the challenges of pinpointing elements in large, complex graphics. Aligned with the broader objectives of this dissertation, the study not only validated the Sonoice UI but also explored additional factors, such as the influence of graphic complexity and scalability on other applications.

Participants

Ten BVI participants (four females, six males; Table 4.3) were recruited from Osnabrück via the local blind association, BVN. Interested individuals were provided with study details and participated if they reported a medical diagnosis of visual impairment or blindness, as visual acuity was not directly assessed. Exclusion criteria included being under 18, substance abuse and medical conditions affecting cognition, hearing, communication, touch, or motor skills. The University of Osnabrück ethics committee approved the study, and all participants provided informed consent. While statistical analysis by subgroup is not feasible due to the unbalanced sample size, participants were categorised based on self-reports into three groups: two as congenitally blind (CB), five as late blind (LB), and three as visually impaired (VI). Participants' experiences with audio-driven pinpoint navigation user interfaces were also collected.

Table 4.3.: Participant demographics and experience with navigation user interfaces (P1-P10).

Users	Gender	VI Type (VA)	Age	Experience with Navigation UIs
P1	male	VI (< 6/60)	65+	-
P2	male	LB (< 3/60)	65+	yes
P3	female	LB (< 3/60)	45 – 64	yes
P4	male	LB (< 3/60)	45 – 64	yes
P5	female	LB (< 3/60)	65+	-
P6	male	VI (< 6/60)	45 – 64	-
P7	female	CB (< 3/60)	18 – 45	yes
P8	male	CB (< 3/60)	18 – 45	yes
P9	female	LB (< 3/60)	65+	-
P10	male	VI (< 6/60)	45 – 64	yes

Visual acuity (VA) levels defined by the WHO [3].

Materials - Graphics

A total of twelve audio-tactile SVG-based graphics were used to learn and evaluate the pinpoint navigation strategies (Figure 4.13). For the learning phase, four graphics were sourced from the open-source ProBlind database [233], while eight new graphics were explicitly designed for the testing sessions, all adhering to the ProBlind layout.

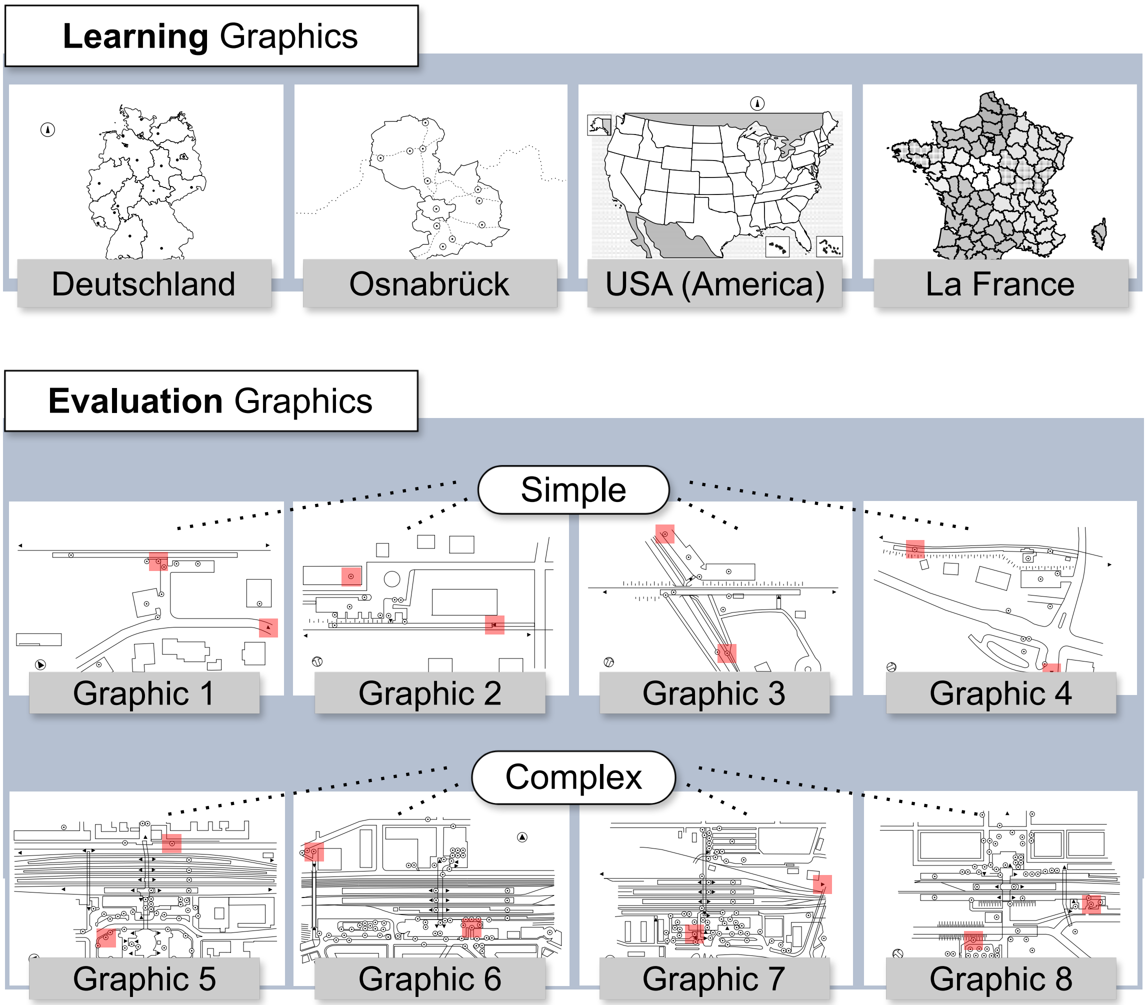

Figure 4.13.: Graphics used to assist participant learning (top) and evaluate the pinpoint navigation strategies (bottom) in this study. The red squares demarcate the target-spot elements participants were required to locate during the testing session. These squares were enlarged to three times their original size in this figure to facilitate ease of viewing. For clarity, the blue targets and QR code from the Problind database layout have been intentionally omitted from this figure.

To facilitate understanding and learning of the pinpoint navigation strategies, four original graphics from the ProBlind database were used: *Deutschland*, *Osnabrück District*, *La France*, and *United States of America*, each in its respective language (German, French, or English). Deutschland and Osnabrück District were selected to provide users with a familiar regional context, helping to simplify the explanation of navigation UIs. In contrast, *La France* and *United States of America* were chosen for their popularity and to provide different, engaging perspectives while showcasing the customisation and scalability of the Problind database. Given the interest shown by BVI users in map representations in previous studies [240, 210, 95], these graphics were selected to enhance the engagement and effectiveness of the user-interface learning experience.

To evaluate the pinpoint navigation strategies, eight graphics representing actual train station floor plans across Germany were designed (Graphics 1 to 8). These graphics are divided into two categories, simple train stations and complex train stations, to assess whether the navigation UI performs independently of graphic complexity and context. The complexity is determined by the total number of spot elements, which are either small circles or triangles SVG elements, each with a square annotation area of 10 mm by 10 mm. The annotation indicates the region where the fingertip must be placed to access the audio information. Graphics 1 to 4 depict simple train stations, each with an average of 14 spot elements, while graphics 5 to 8 represent more complex train stations, with an average of 79 spot elements. For each graphic, two spot elements were designated as target points for the user to pinpoint during the evaluation. Such targets were spaced equally apart from each other across all graphics, aiming to maintain consistency. In addition to spot elements, the train stations feature audio labels for platforms, train tracks, streets, and external buildings. The spot elements mark key points of interest in the stations, such as entrances, elevators, bus stops, cafes, information points, and bicycle racks. Train station representations were chosen because of their relevance in the BVI community [209, 95], and mobility and orientation solutions remain less developed for tactile graphic readers and 2D refreshable tactile pin displays compared to other fields [237]. These graphics, including the addition of audio labels, were created using the open-source software Inkscape on an SVG ProBlind layout template. All SVG elements were rendered in black with a stroke width of 0.5 mm. The final graphics were uploaded to the database, printed on swell paper, and processed using the PIAF (Tactile Image Maker) heating chamber [223].

4.3.1. Experimental Setup

The study followed a within-subjects design, where each participant tested all four pinpoint navigation strategies. Since the number of participants was insufficient to cover all 24 unique order combinations, a random assignment of UI order was used. For the same reason, the order of the eight evaluation graphics was also randomised. Each participant completed the study individually in a single 90-minute session. Further details on the task can be found in the supplementary material (see Appendix B.1). Figure 4.14 illustrates the step-by-step progression of the experimental procedure, ensuring clarity and enhancing comprehension of the distinct phases involved.

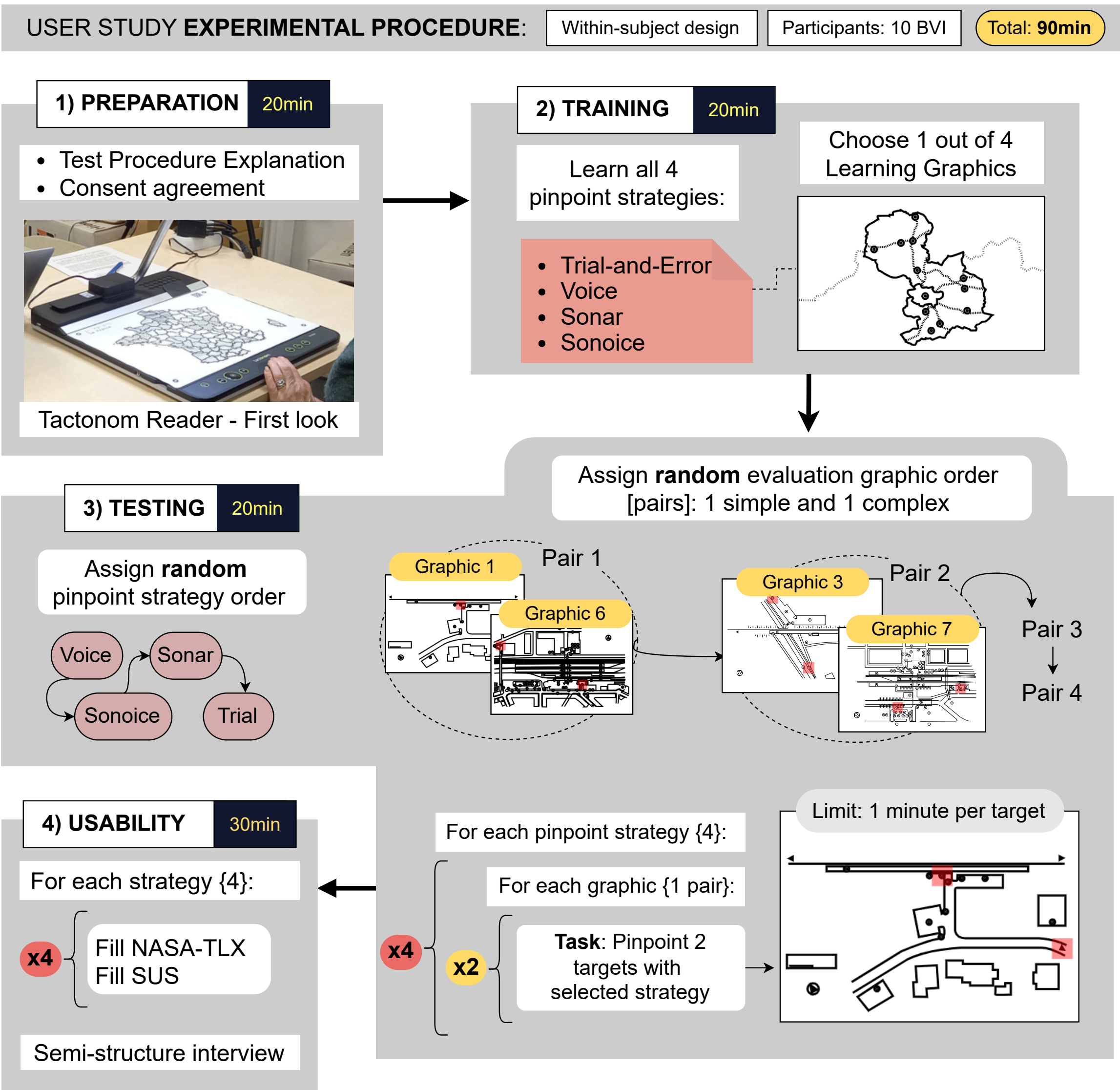

Figure 4.14.: Experimental Procedure: Sonoice, combining sonification with voice

Study Procedure - Preparation

The study began with a briefing on its purpose and procedures. Participants then provided consent, either by signing a form or giving verbal agreement, which was audio recorded. They were also reminded of their right to withdraw from the study at any time without the need for explanation. Afterwards, participants had 15 minutes to familiarise themselves with the Tactonom Reader device (see Section 3.1.1), including its dimensions, camera-based finger detection, tactile UI buttons, and graphic reloading workflow. The 90-minute session duration was insufficient to explore additional functions of the Tactonom Reader.

Study Procedure - Training and Testing

After their initial introduction to the Tactonom Reader, participants were instructed to learn the four pinpoint strategies—trial, sonar, voice, and sonoice—one at a time. Based on their interest and motivation, they chose one of four learning graphics to learn all navigation strategies. Training trials could be repeated for up to five minutes per strategy. Once all strategies were learned, the order of pinpoint strategies and graphic pairs was randomly assigned. For each strategy, participants were required to pinpoint two set targets for each of the two evaluation graphics, totalling four targets per strategy. A 60-second time limit was set for pinpointing each target. This procedure was repeated for the remaining three strategies and their corresponding graphic pairs.

Study Procedure - Usability

The final part of the experiment involved completing a NASA-TLX and SUS questionnaire for each pinpoint strategy. This was followed by a global semi-structured interview to evaluate the Tactonom Reader's usability and determine how practical the navigation strategies were in assisting BVI users in pinpointing elements in tactile graphics.

Data Analysis Methodology

A mixed-methods approach was used, combining quantitative data with qualitative insights from semi-structured interviews and user comments. The investigation analysed efficiency (trial duration) and user satisfaction (SUS and NASA-TLX scores), with these measures serving as the dependent variables. Statistical analysis was conducted using repeated-measures ANOVA to evaluate differences across the strategies, followed by pairwise t-tests to identify significant differences between individual strategy pairs. Questionnaires (NASA-TLX and SUS) were assessed using normalised scores, while subjective data from interviews were analysed using descriptive statistics and thematic analysis. Although no further statistical analysis was conducted on subgroups, results include data categorised by visual impairment type: CB (congenitally blind), LB (late blind), and VI (visually impaired). Participant comments were linked to an identifier, visual impairment type, and preferred navigation strategy (e.g., P7, CB, Sonar).

4.3.2. Results

The study primarily aimed to evaluate and validate the four distinct navigation strategies. Section 4.3.2.1 examines navigation efficiency, while section 4.3.2.2 looks at user satisfaction. Additionally, the analysis assessed the impact of graphic complexity (section 4.3.2.3) and the expanding context applications of the navigation strategies (section 4.3.2.4).

The figures in this section incorporate specific markers and specifications to improve the clarity of the data. Boxplots display the medians as solid lines. Black markers represent the medians of each subgroup of visual impairment type for each boxplot distribution: circles for CB (Congenitally Blind), squares for LB (Late Blind), and stars for VI (Visually Impaired). Outliers are illustrated as grey diamonds.

Efficiency of Pinpoint Navigation Strategies

To assess efficiency, the distribution of trial durations across the four pinpoint navigation strategies (trial-and-error, sonar, voice, and sonoice) was examined. The mean elapsed time required by participants to pinpoint one target element was 57.85 ± 8.04 s for trial-and-error, 20.68 ± 8.99 s for Sonar, 17.58 ± 9.50 s for Voice, and 15.48 ± 8.91 s for Sonoice (figure 4.15). Remarkably, among the 40 trials conducted using the trial-and-error approach, only four trials (10%) were successfully finished within the designated time limit of 60 seconds, while the remaining trials reached the maximum duration allowed.

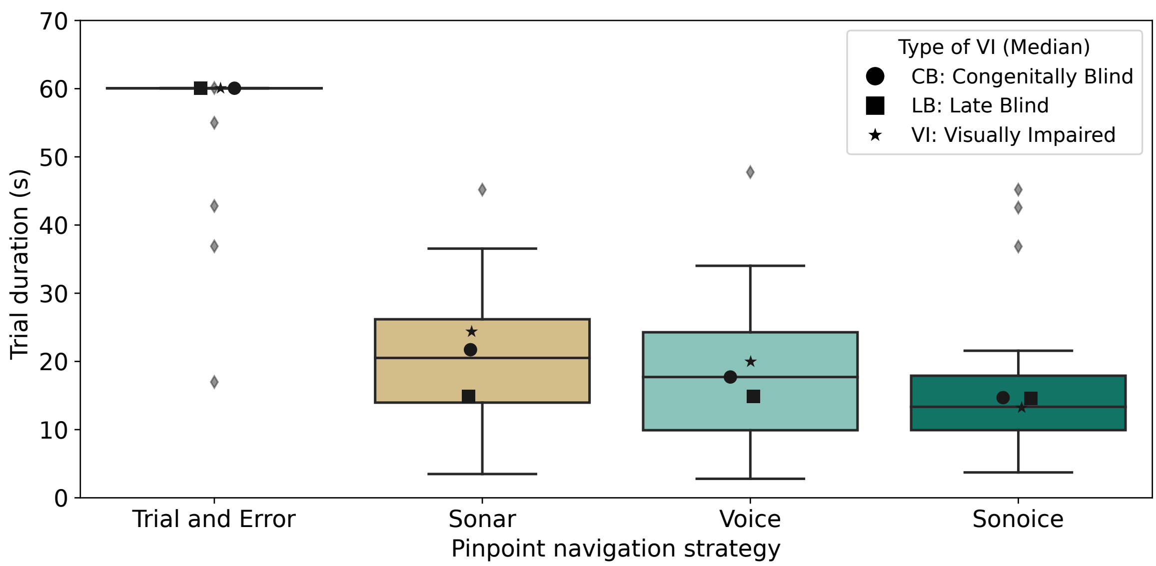

Figure 4.15.: Efficiency analysis. Trial duration distribution (in seconds) across the four pinpoint navigation strategies (trial-and-error, sonar, voice, and sonoice).

A repeated measures ANOVA statistical test with $\alpha = 0.05$ was used to assess potential significant variations in mean trial durations across the different strategies. Results showed a statistically significant difference between the mean trial durations of the four strategies ($F(3, 27) = 139.5827$, $p < 0.001$). The calculated F-value (139.5827) exceeded the critical F-value (2.9604) for the test, leading to the rejection of the null hypothesis. These findings reveal a significant difference in the mean trial durations among the four pinpoint navigation strategies.

To determine the specific nature of the disparities between the navigation strategies, pairwise t-tests were performed on the average trial duration for each strategy pair. The results revealed significant differences between several pairs of strategies. The trial strategy exhibited substantial differences compared to the Sonar ($t = -12.83$, $p < 0.001$), Voice ($t = -18.00$, $p < 0.001$), and Sonoice ($t = -22.78$, $p < 0.001$) strategies, indicating that the trial strategy was significantly less efficient than the other three. Yet, no significant differences between the Sonar and Voice ($t = -1.12$, $p = 0.291$), between the Voice and Sonoice methods ($t = 1.22$, $p = 0.255$), and between the Sonar and Sonoice methods ($t = -1.95$, $p = 0.083$) were found.

Notably, the Sonoice method exhibited consistently lower mean trial durations than the other strategies, although statistical tests did not yield significant differences. While these findings suggest the potential higher efficiency of Sonoice in pinpointing elements in tactile graphics, further data would be necessary to determine whether this effect reaches statistical significance.

User-satisfaction Analysis

To compare the four navigation strategies further, qualitative and quantitative feedback from semi-structured interviews, NASA-TLX, and SUS questionnaires was examined.

Regarding subjective workload, results from the NASA-TLX questionnaires showed that the mean normalized (0-100) scores (± standard deviation) for the Trial-Error, Sonar, Voice, and Sonoice strategies were 33.67 ± 26.90, 5.50 ± 5.95, 10.00 ± 13.45, and 8.75 ± 9.21, respectively (Figure 4.16-left plot). These results suggest that the trial strategy may have provoked a higher workload for participants since its average score is at least three times bigger than any other navigation strategy. To understand if there was any significant difference between the user-interface strategies for pinpoint elements (Sonar, Voice, and Sonoice), a repeated measures ANOVA statistical test with $\alpha = 0.05$ was performed. Results indicated no substantial disparity in the mean NASA-TLX score across the navigation strategies ($F(2, 18) = 0.394$, $p = 0.983$), suggesting that these are equally effective in overall user workload.

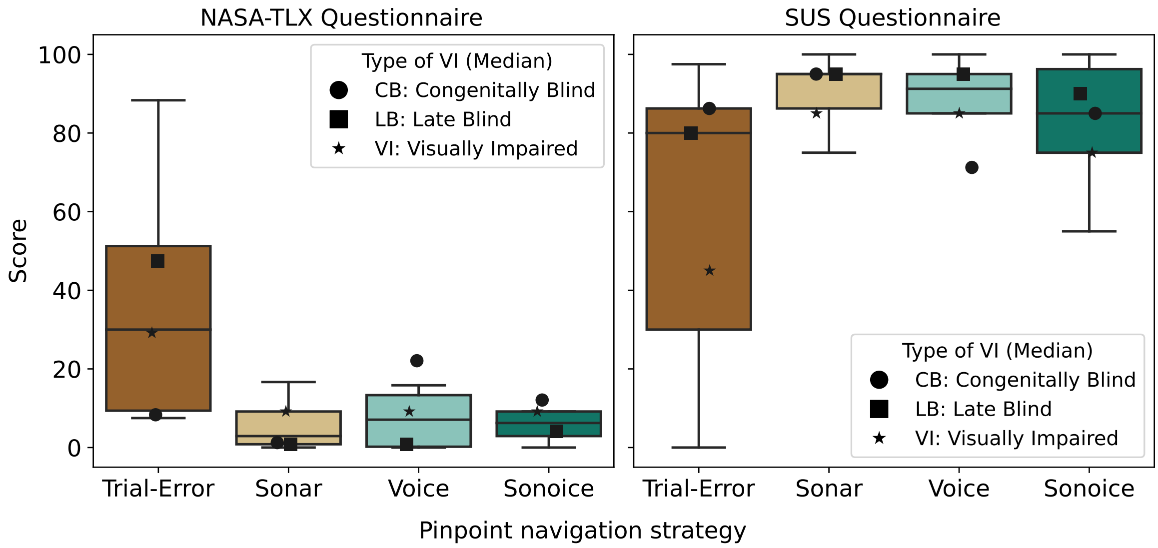

Figure 4.16.: Comparison of subjective workload and satisfaction ratings across pinpoint navigation strategies. The left plot shows the NASA-TLX scores, while the right plot shows the SUS scores for the trial, Sonar, Voice, and Sonoice strategies.

Regarding overall satisfaction, results from the SUS questionnaires showed that the mean normalized (0-100) scores (± standard deviation) for the Trial-Error, Sonar, Voice, and Sonoice strategies were 59.75 ± 36.39, 88.50 ± 13.95, 84.00 ± 17.96, and 83.25 ± 14.67, respectively (Figure 4.16 - right plot). The trial-and-error strategy had the lowest mean SUS score, indicating it was the least satisfactory among users. The other three strategies all received an average score not only above the average (68) but above 80, considered a high score by existing literature [23, 258]. These results indicate that participants rated the Sonar strategy as the most satisfactory, followed by the Voice and Sonoice strategies. To determine if there were any significant differences between the SUS scores of the user-interface navigation strategies (Sonar, Voice, and Sonoice), a repeated measures ANOVA statistical test with $\alpha = 0.05$ was performed. The results showed no significant difference between the strategies ($F(2, 18) = 0.780$, p-value = 0.473).

Although the NASA-TLX and SUS questionnaire analysis did not reveal significant differences between the Sonar, Voice, and Sonoice strategies, these measures are subjective and do not fully capture all aspects of user satisfaction. Therefore, it is essential to consider the valuable qualitative feedback obtained from the semi-structured interviews to gain a deeper understanding of participant's preferences and experiences with the navigation strategies. During the interviews, participants were asked about their most and least preferred strategies for pinpointing elements in tactile graphics (figure 4.17). To acquire further insights not only into overall subjective evaluation but also to elucidate the underlying rationale behind each decision, user comments were included in the analysis.

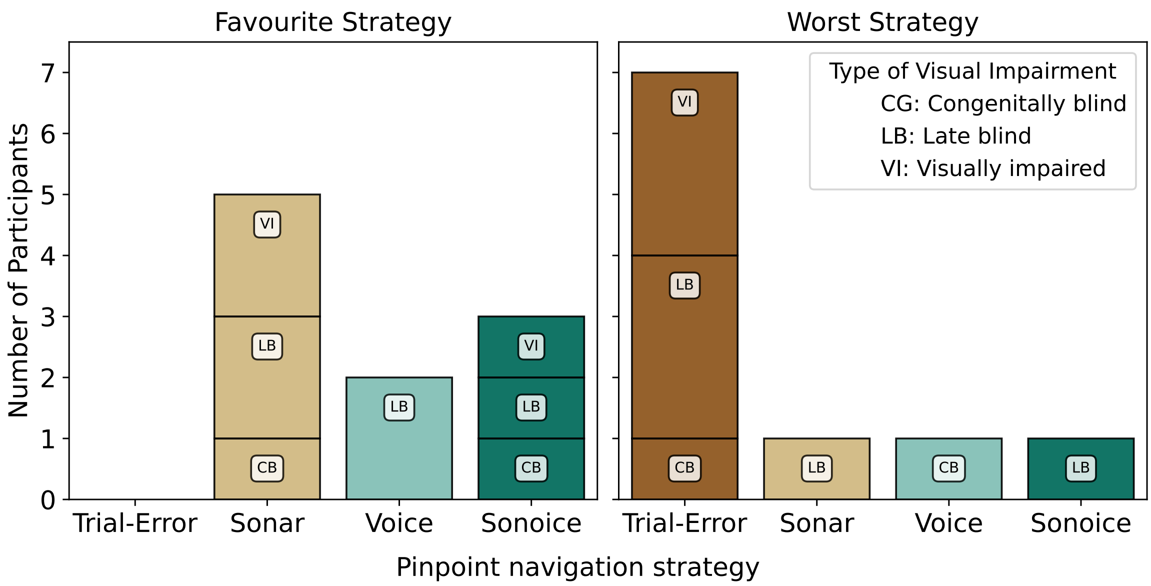

Figure 4.17.: Distribution of favourite and worst pinpoint strategies reported by participants (10 in total) during semi-structured interviews. Each bar chart is segmented by the type of visual impairment, denoted by CB, LB, and VI votes.

Among the participants, the Sonar UI emerged as the most highly rated strategy, receiving a total of 5 out of 10 votes as the favourite choice (figure 4.17). Participants provided positive feedback regarding its design, highlighting its familiarity, responsiveness, and intuitive nature: "The Sonar because it uses a principle that I am familiar with and it feels more responsive and more intuitive" – (P7, CB, Sonar), "Sonar (voices are difficult to hear when there are other people around). It is well distinguishable from natural sounds" – (P10, VI, Sonar), "Sonar because it is super quick and intuitive!" – (P4, LB, Sonar), "My favourite was Sonar, but Sonoice is still a great option although it uses a lot of information which can confuse you!" – (P1, VI, Sonar).

The Sonoice UI was the second most highly rated strategy, receiving a total of 3 out of 10 votes as the favourite choice (Figure 4.17). Participants acknowledged the benefits of utilising a combination of sonification and voice to obtain more detailed information and accurately pinpoint the target position: "Sonoice is direct guidance combined with fast guidance. With more information, you get there faster! It depends a bit on how well you're able to multitask, but it has high potential!" – (P6, VI, Sonoice), "Most of all, Sonoice because it first provides the general direction and then more fine-tuned details!" – (P8, CB, Sonoice), "Sonoice because you get a much better overview of the environment in general and the spatial relationships." – (P2, LB, Sonoice).

The remaining participants (2 out of 10) preferred the Voice UI (figure 4.17). These participants found the Voice solution to be straightforward and responsive: "The Voice method is very specific and straightforward!" – (P3, LB, Voice), "The Voice since it is directly interpretable and can change quickly." – (P9, LB, Voice).

The trial-and-error strategy was the least favoured by the majority, with 7 out of 10 participants expressing dissatisfaction (Figure 4.17). Users highlighted limitations, such as uncertainty, feeling helpless, and tediousness: "Just with trial and error, you are limited! I feel helpless and don't know what to do! It is uncomfortable and feels more like a TOY than a tool." – (P3, LB, Voice), "It is tedious to press the button constantly in the trial and error approach" – (P1, VI, Sonar), and "The trial and error strategy is difficult to apply in the context of finding an element! Requires a lot of time and pressing!" – (P5, LB, Sonar). Despite its flaws in pinpointing elements, participants acknowledged the trial-and-error strategy's usefulness for obtaining a first overview of the graphic content: "The worst was trial-and-error to localise but to explore it's amazing! It should be the first step to explore with this mode to get an overview" – (P8, CB, Sonoice) and "The trial-and-error strategy would be ideal for exploring as part of mobility training!" – (P2, LB, Sonoice).

Each of the three UI strategies (sonar, voice, and sonoice) received one vote as the least favourite (figure 4.17). In Sonar navigation, participants mentioned the difficulty in realising they were moving in the wrong direction, "Sonar was the worst! It took me super long to change directions and to realise when I was going in the wrong direction. I could not react quickly enough to avoid going in the wrong direction." – (P9, LB, Voice). The Voice was criticised for requiring excessive mental effort in interpreting the clock system, "Voice is the worst because I needed to think too much about the clock and where the 3 hours is located!" – (P7, CB, Sonar). Users also found the Sonoice strategy overwhelming, "Sonoice is too much, and concentration is hard to keep!" – (P4, LB, Sonar).

Based on the analysis of the NASA-TLX, SUS, and semi-structured interviews, all navigation UI strategies have demonstrated their usefulness, exhibiting statistically higher satisfaction levels compared to the standard trial-and-error approach. All ten users unanimously agreed that they found at least one of the three navigation UIs more valuable than the trial-and-error method for locating elements in tactile graphics. Furthermore, all participants highly endorsed the navigation user interfaces to the BVI community, "I absolutely prefer the navigation modes, and I think the Tactonom with these would be a great addition to my current devices!" – (P10, VI, Sonar), "I would use them. I would retrieve much more information from the graphics with the navigation strategies!" – (P8, CB, Sonoice).

Results revealed that while the Sonoice UI received positive feedback from participants, sufficient evidence to conclude that it consistently outperformed the other strategies regarding user satisfaction was not gathered. Notably, participants' preferences and experiences varied across the different navigation strategies, and no significant differences were found in overall user satisfaction between the Sonar, Voice, and Sonoice strategies according to the collected data.

Overall, findings revealed that the implemented UIs significantly improved user satisfaction compared to the traditional trial-and-error approach. Based on these results, pinpoint strategies hold considerable potential to enhance the accessibility and usability of tactile graphics for individuals with BVI. Further research and larger sample sizes may be necessary to explore potential differences in satisfaction with more detail.

Unveiling the Influence of Graphic Complexity

Understanding the efficiency of navigation strategies in tactile graphics entails examining the impact of graphic complexity on user performance. Surprisingly, no significant difference was found in the mean trial duration between complex graphics (27.10 ± 20.28 s) and simple graphics (28.69 ± 18.86 s) (figure 4.18). These results suggest that graphic complexity does not significantly impact the time required for pinpointing elements, holding true regardless of the navigation interface (Sonar, Voice, Sonoice) or the trial-and-error approach.

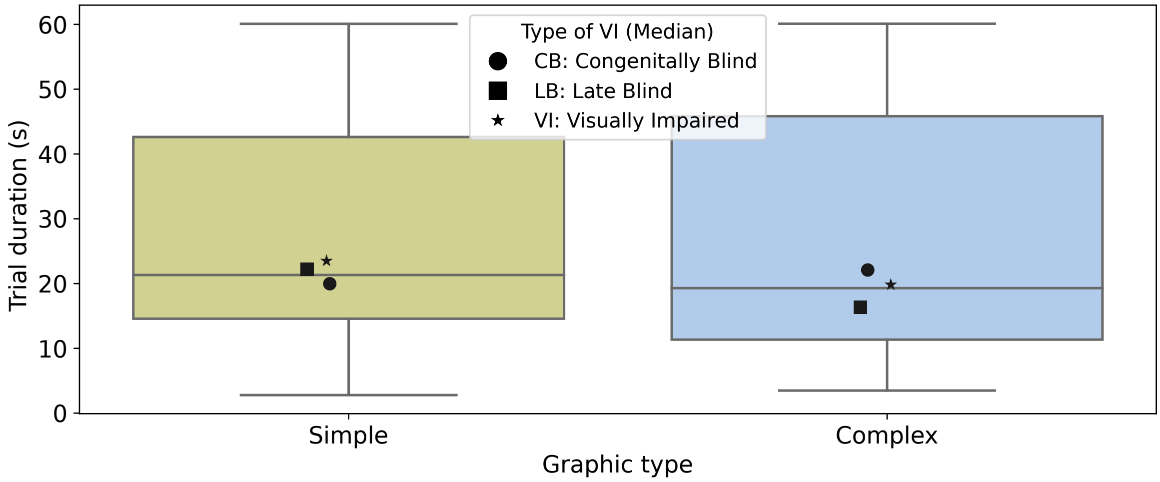

Figure 4.18.: Distribution of trial durations (s) per graphic type (Simplex and Complex).

To gain deeper insight into the impact of graphic complexity on user performance, the research was expanded to examine each navigation's efficiency on simple and complex graphics separately. Subsequently, the analysis tested specifically whether navigation UIs help individuals with BVI to pinpoint elements in complex graphics more efficiently than the trial-and-error strategy. The results revealed the superiority of the Sonar, Voice, and Sonoice navigation strategies over the trial-and-error approach for complex but also simple graphics. In complex graphics, the mean trial duration was 19.98 ± 9.85 s for Sonar, 16.99 ± 10.39 s for Voice, and 13.53 ± 7.60 s for Sonoice, while the trial-and-error approach had a significantly higher mean trial duration of 57.91 ± 9.63 s. Similarly, in simple graphics, the mean trial duration was 21.39 ± 8.25 s for Sonar, 18.16 ± 8.75 s for Voice, and 17.42 ± 9.86 s for Sonoice, compared to 57.79 ± 6.31 s for the trial-and-error approach (figure 4.19).

These results offer compelling evidence that a navigation UI allows individuals with BVI to pinpoint elements in both complex and basic graphics more efficiently than the trial-and-error method. This suggests that the UIs could be effectively applied beyond complex graphics, highlighting their potential to enhance accessibility and usability across various tactile graphics of differing complexity.

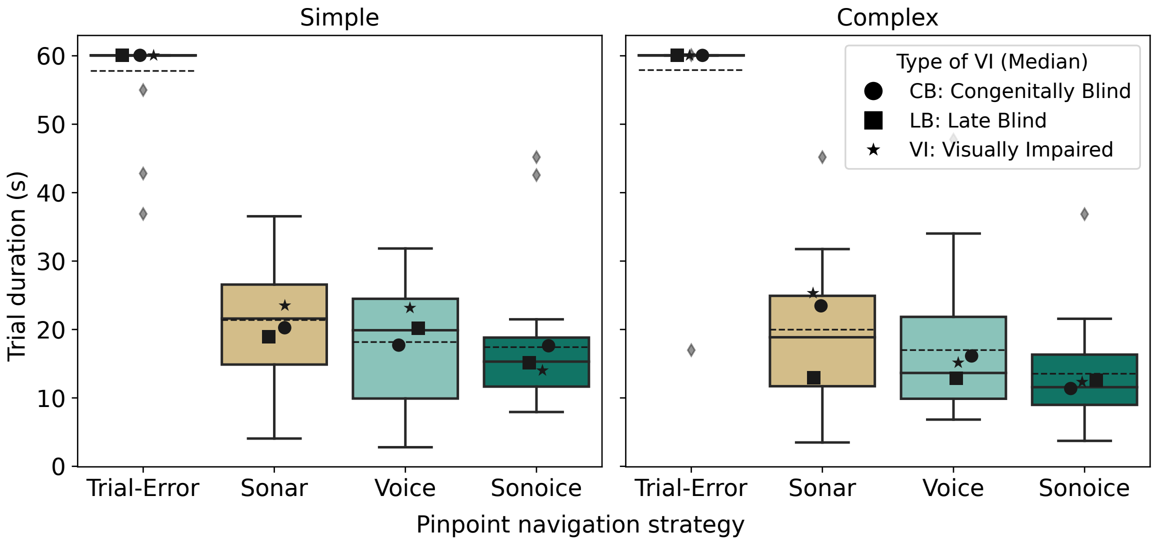

Figure 4.19.: Distribution of trial durations (s) across graphic type and pinpoint navigation strategy.

Expanding Applications of Pinpoint Navigation Interfaces

Pinpoint navigation strategies, while valuable for locating elements in tactile floor plans, have broader potential applications. In the semi-structured interviews, participants discussed how such interfaces could be contextualised within different assistive technology sectors. Their insights suggested a wide range of possible uses, such as emergency floor plans, educational graphics, public services, navigation apps like Seeing AI, country maps, and even everyday devices like washing machines, where users could quickly locate specific settings. One participant remarked, "In floor plans or countries maps. It would be amazing to use it in washing machines and find a certain setting." – (P5, LB, Sonar). Participants also pointed out the potential benefits of combining pinpoint navigation with on-site sensor-based navigation technologies [92, 235, 263, 38], like the FeelSpace naviBelt: "Use navigation modes for practical preparation and then the FeelSpace belt for mobile applications." – (P10, VI, Sonar). This approach suggests that pinpoint navigation could be leveraged for mobility training, mental mapping of dynamic environments, and pre-trip preparation, with sensor-based systems offering real-time support during navigation.

Seven out of ten participants reported having no prior experience with technologies similar to the Tactonom Reader, suggesting that this type of technology remains in its early stages and is not yet widely accessible. These user evaluations emphasize the innovative and developing nature of pinpoint navigation interfaces, highlighting their promise for future integration across various fields and assistive technologies.

4.3.3. Discussion

All UI-based navigation strategies outperformed the trial-and-error approach, demonstrating their superiority and importance in facilitating efficient pinpointing of tactile elements. Among these user interfaces, the Sonoice navigation emerged as the most efficient. Yet, satisfaction ratings were distinct from performance ratings, mirroring findings from previous studies [240] and defying the conventional notion that the most efficient method is necessarily the most favoured. Participant's comments shed light on this peculiarity, "My favourite was Sonar, but Sonoice is still a great option although it uses a lot of information which can confuse you!" – (P1, VI, Sonar), "Sonoice is too much, and concentration is hard to keep!" – (P4, LB, Sonar). Understanding these contrasting views and their connection to performance requires a more in-depth discussion of user preferences and subjective experiences. The discussion also addresses the exploratory benefits of the trial-and-error approach and examines the impact of graphic complexity on pinpointing elements.

Divergence between Performance and User Satisfaction

High Performance: Such divergence between performance and satisfaction is particularly evident in the Sonoice navigation. Despite not receiving user satisfaction ratings as high as the Sonar UI, the Sonoice navigation exhibited the lowest mean trial duration during the experiments. This raises the question: how could Sonoice achieve higher efficiency despite lower satisfaction ratings? The answer may reside in the combination of the efficiency advantages of Voice and Sonar UIs. Voice navigation offers directional guidance but lacks distance cues and may blend with background sounds: "voices are difficult to hear when there are other people around" – (P10, VI, Sonar), as shown in prior research [200, 87]. Sonar navigation provides proximity feedback but relies on users interpreting pitch variations to determine the correct movement direction. Sonoice UI leverages the advantages of both Sonar and Voice navigation by incorporating directional speech guidance together with proximity sonification, providing users with a comprehensive and efficient navigation experience: "Sonoice is direct guidance combined with fast guidance. With more information, you get there faster!" – (P6, VI, Sonoice). Recent studies have shown that integrating sonification with voice feedback has yielded favourable results across multiple assistive interfaces [11, 106, 12, 5], suggesting that such a joint combination can also enhance the efficiency of tactile graphics exploration.

High User Satisfaction: Although it emerged as the most efficient method, the Sonoice method was not the most preferred strategy. A resolution to this is that Sonoice provides more information than the other two UIs, which some users found overwhelming: "My favourite was Sonar, but Sonoice is still a great option although it uses a lot of information which can confuse you!" – (P1, VI, Sonar). Another factor could be that assistive technology generally relies on either voice or sonification approaches [93, 119, 108, 159, 61], meaning that combining both methods can create unfamiliarity or hesitation among users.

The impact of familiarity and user preference is highlighted in the Sonar navigation, as, despite not being the fastest approach, it achieved the highest satisfaction rate: "The Sonar because it uses a principle that I am familiar with" – (P7, CB, Sonar), "Sonar because it is super quick and intuitive!" – (P4, LB, Sonar). These findings underscore the influence of participants' prior experiences and contextual factors in shaping their preference for a particular navigation UI, aligning with similar observations in prior research [113, 13, 237, 200]. Nevertheless, it's worth noting that users received only 5 minutes of training per strategy. With extended training, users could potentially become more familiar with and less overwhelmed by the Sonoice approach, changing this investigation outcome. Moreover, these potential changes are also subject to individual differences and visual impairment types, which were not weighted in this research.

Trial-and-Error Value in Tactile Graphics Exploration

While being the least favoured and least efficient in pinpointing elements, the trial-and-error approach still proved helpful for users. It allows BVI individuals to familiarise themselves with the layout and content of the graphic, providing a starting point for further interaction and interpretation: "The worst was trial-and-error to localise, but to explore it's amazing! It should be the first step to explore with this mode to get an overview" – (P8, CB, Sonoice). As a result, such method is used in numerous 2D tactile graphic readers [202, 201, 59, 110, 56, 112, 181, 123, 124, 83], highlighting its significance in facilitating exploration and providing an overview. While the trial-and-error strategy may not provide direct and precise guidance to pinpoint elements, given its value in facilitating initial exploration, the trial-and-error functionality should be included for accessing tactile graphics in assistive technologies. By recognising its role and benefits, developers can ensure that users with BVI can access a range of strategies that cater to different aspects of their exploration needs, enhancing their overall experience and access to 2D information.

Assessing Complexity in Train Station Floor Plans

Regarding graphic design, results revealed that the choice of navigation UI strategy (Sonar, Voice, and Sonoice) did not yield significant differences in performance between simple and complex graphics. This indicates that the implemented UI strategies demonstrated consistent effectiveness regardless of the complexity of the tactile graphic. However, the trial-and-error approach presented a different outcome, as most of the samples reached completion within the given time limit. It is worth considering that if the trial duration had not been restricted to 1 minute, we might have observed contrasting results using the trial-and-error method between simple and complex graphics. These findings shed light on the time-consuming nature of interacting with seemingly "simple" graphics, highlighting the inherent challenge individuals with BVI face in accessing and comprehending two-dimensional information [102].

4.4. CONCLUSION AND FINDINGS

Locating elements on tactile surfaces remains a significant challenge for individuals with BVI, and no ideal solution has yet emerged. This is especially true for emerging 2D tactile graphic readers, which, despite their potential to revolutionise access to 2D data, rely on large surfaces that complicate pinpointing elements. To advance this technology and address the research gap, a generic, efficient, scalable solution is needed.

A dynamic Axis-based navigation UI was developed through a human-centred design and tested against the standard Voice and Sonar UIs in the first study involving 13 BVI participants. While promising, the proposed solution fell short in addressing the challenge, having low user ratings and being associated with slower times. The key factor contributing to this was the difficulty users faced in maintaining a straight line while navigating, notably evident on the large surfaces of tactile graphic readers, where such precision is crucial for effective interaction with Axis navigation. Sonar navigation addressed this issue by enabling diagonal movement, but Voice still emerged as the most efficient and preferred solution. Nevertheless, some users found Voice navigation repetitive and annoying, highlighting the impact of users' preferences and the need for a balance between satisfaction and performance. Findings also highlight that irregular spatial arrangement of tactile points can mislead users' movements and negatively impact efficiency, especially in Axis and Voice navigation, emphasising the crucial role of tactile graphic design.

Following a human-centred design, a new UI solution, Sonoice navigation, was proposed to address the users' difficulties by leveraging the advantages of both sonar and voice navigation. A user study with 10 BVI participants evaluated Sonoice, Voice, Sonar, and trial-and-error strategies for pinpointing elements in tactile floor plans of varying complexity. All UI-based solutions significantly outperformed the trial-and-error method, which failed to assist users in pinpointing the majority of elements within the time limit, showcasing the importance of implementing tailored user interfaces to address this key challenge. Results revealed that such UI solutions did not yield significant performance differences between simple and complex floor plans. Sonoice proved to be the most efficient solution by using directional guidance and proximity feedback. Yet, user preferences varied—some quickly recognised its potential, interpreting it as "SO NICE!" while others felt overwhelmed by its unfamiliarity, experiencing it more as "SO NOISE!" These findings underscore the crucial role of acquaintance and prior experience in UI design. Thanks to its scalable design, Sonoice not only advances tactile graphic readers but also extends to other assistive technologies, including 2D refreshable tactile pin displays and various application domains, further empowering individuals with BVI and fostering a more accessible world.

These findings offer valuable insights into the design of audio-tactile navigation systems. To deepen our understanding, we now turn to Research Question 1 and its sub-questions, each addressing a critical aspect of accessible pinpoint navigation on 2D tactile surfaces for BVI users.

Answering Research Question 1

RQ1.1: To what extent can current state-of-the-art audio-tactile UIs assist BVI individuals in efficiently pinpointing elements on large 2D tactile surfaces?

Based on the first evaluation study, we conclude that state-of-the-art dynamic UIs effectively assist BVI individuals in pinpointing elements on large 2D tactile surfaces (see Section 4.2). Notably, voice-based cardinal-direction navigation enabled participants to pinpoint targets on A3-size surfaces in a mean time of 23.3 seconds. A second evaluation study confirmed that all UI-based navigation strategies outperformed the trial-and-error approach, highlighting their effectiveness in facilitating efficient pinpointing (see Section 4.3). Among the SOTA interfaces, clock-based voice navigation was the most efficient, with participants pinpointing targets in a mean time of 17.58 seconds.

RQ1.2: What key design factors contribute to an efficient, well-balanced dynamic audio-tactile UI for assisting BVI users in pinpointing elements on large 2D surfaces?

Findings from the first evaluation concluded that UIs relying heavily on straight movements (axis-based) are not effective for BVI users, as they struggle with maintaining straight hand motions, especially on large surfaces (see Section 4.2). In contrast, Sonoice navigation has proven to help BVI users locate targets more efficiently on large surfaces (see Section 4.3). We believe that integrating speech and sonification, as seen in Sonoice navigation, are key design factors for efficiently assisting BVI users in pinpointing elements. While some users found it overwhelming, it still received the second-best user satisfaction rating, even though users were using this method for the first time. This demonstrates the potential of Sonoice navigation to appeal to a diverse user base, including those who prefer speech-based interactions and those more inclined toward sound-driven or gamified UIs.

RQ1.3: How does graphic complexity impact the performance and effectiveness of pinpoint navigation user interfaces?

Participants took longer to pinpoint targets on one specific graphic in the first study, with a high mean time of 51.7 seconds (see Section 4.2). This was attributed to the graphic's uneven tactile information arrangement, which can mislead the user's direction, especially in the axis and voice-based methods, where users follow straight directions. The second usability study showed no significant differences (even for voice-based) in efficiency and effectiveness between simple and complex graphics (see Section 4.3). Overall, graphic complexity does not significantly affect the efficiency or effectiveness of navigation UIs unless the graphic has uneven tactile points that mislead users into following diagonals instead of straight lines, particularly impacting direction-based UIs.

5. CRAFTING 2D DYNAMIC LINE CHARTS EXPLORATION

Line charts are fundamental tools for visualising trends and comparing large amounts of data in several domains. Despite technological advancements, individuals with BVI still face significant challenges in interpreting complex real-world line charts, as state-of-the-art tactile graphic reader approaches are effective only for straightforward charts, with their applicability to complex ones remaining unexamined. To tackle this challenge, a Trigger-Trace Line Exploration UI was proposed and evaluated against the state-of-the-art Tap-to-Hear Exploration UI in a preliminary study with four BVI individuals. Results showed no significant improvement in effectiveness, and while both UIs performed well with simple charts, they struggled with complex ones. Key limitations included the inability to determine line boundaries and the lack of an intuitive method for recognising intersections. Addressing these issues, a dynamic human-centred solution—Melodic Line Tracing Exploration—is proposed, featuring a synth melody environment, pitch trace guidance, and line boundary feedback. A second user study with 10 BVI participants revealed that the Melodic solution outperformed the standard tap-to-hear approaches, empowering users (beginners and advanced) to understand complex line charts with high intersections and fluctuations effectively. By the end, users perceived the line charts as much less complex, underscoring the interface's significant impact on reshaping their perspective of graphic complexity.

This chapter includes content from a publication in PETRA 2023 [239].

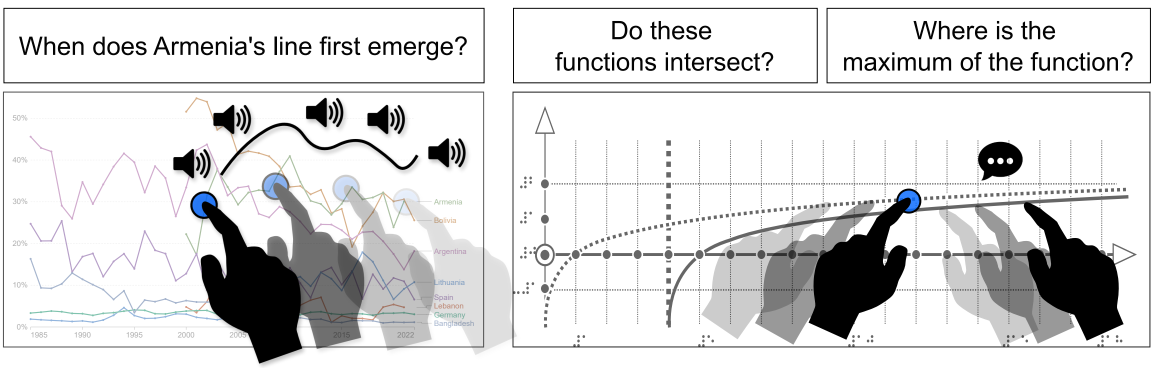

Figure 5.1.: Contextual Applications of **Learning and Exploring Tactile Line Charts**

5.1. GRASPING AND EXPLORING LINE CHARTS

Two-dimensional (2D) and graphical data are integral to our daily lives, from our early education years, when we explore learning school graphs, to advanced visualisations like neural network architectures. Among these, **line charts** stand out as one of the most fundamental forms of graphical representation, offering a straightforward and efficient way to track trends, compare large amounts of data, and analyze patterns over time or across categories [21]. Their ability to reveal fluctuations, highlight correlations, and support predictive analysis makes them essential in several fields, including finance, project management, education, scientific research, news reporting, and website analytics [105, 152]. As a widely recognized and intuitive format, line charts serve as a universal language for data interpretation, shaping how we understand and communicate complex information (Figure 5.1).

However, despite technological advancements and the emergence of promising solutions like tactile graphic readers and 2DRTP displays, interpreting and understanding complex, real-world line charts remains a key challenge for individuals with BVI [198]. While line charts are widely used across several fields, their inherently visual nature creates barriers for BVI individuals. Accessible design struggles to keep pace with the growing reliance on visual data [165, 182, 152, 275], and even professional institutions producing assistive materials face difficulties in adapting such data into usable, accessible formats [228, 229]. As a result, BVI users often depend on colleagues or screen readers to interpret raw data tables, limiting their ability to autonomously analyze trends, compare multiple lines, and extract meaningful insights from line charts [105]. Overcoming these challenges is essential to ensuring equal access and fostering inclusivity in an increasingly data-driven world [165, 153].

This research investigates human-centred dynamic audio-tactile UIs to support BVI individuals in learning and exploring realistic, highly complex line charts. The focus was on designing UI solutions that are efficient across diverse user preferences and experience levels while also being scalable to both tactile graphic readers and 2DRTP displays. This work aligns with the broader goal of advancing graphic accessibility, which is central to this dissertation.

5.1.1. Method-Interface Spectrum

Extensive past research has explored diverse solutions for assisting individuals with BVI in understanding and interpreting tactile line charts. These efforts encompass five categories: speech interfaces (including natural language), sonification, multimodal speech-sonification, tactile graphics, and multimodal audio-haptic interfaces. An in-depth literature review was conducted to explore the key advantages and limitations of each solution, considering applications not only on tactile graphic readers but across a broader spectrum of assistive technologies.

Speech interfaces

One of the most popular and straightforward methods in assistive technology to help BVI users learn line charts is to use alternative text descriptions [198, 222, 276]. This involves screen readers that provide speech feedback, describing the chart type, axes, and its contents. However, while flexible and valuable, text descriptions alone have proven insufficient for conveying all graphical aspects in 2D data [165, 206, 276, 118]. Long descriptions can diminish this problem by describing additional elements, such as intersections and the direction of the line, describing the curve as 'slightly upward' [21]. Nevertheless, verbal descriptions of complex charts often result in lengthy, hard-to-understand explanations that, while valuable, hinder users from analysing trends and exploring the charts autonomously [96, 153, 21].

Beyond text descriptions, more advanced speech interfaces allow users to additionally interrogate graphics with adequate vocabulary (user queries) through keyboard combinations (natural language interfaces) [105]. Some natural language-based interfaces enable users to pose targeted queries about specific portions of the line chart [16], facilitating intuitive data manipulation and enhancing user autonomy [86]. More recently, advancements in this area have integrated large language model (LLM)-based question-and-answer modules, which provide users with on-demand context-aware responses (web search capabilities), enhancing the overall interactivity of the system [122]. While these methods have demonstrated significant value in helping BVI users understand line charts in past user studies, their effectiveness with more complex line charts has yet to be thoroughly explored. Furthermore, it remains an open question whether question-and-answer interactions alone can truly capture the depth and nuance required for full comprehension and interpretation of line charts.

Sonification interfaces

An alternative method to assist individuals with BVI in understanding and exploring line charts is through non-speech sonification interfaces, specifically auditory graphing systems [296]. Digital tools like the *SAS Graphics Accelerator* [37], *Highcharts Sonification Studio* (HSS) [64], and the *SenseMath* [307] leverage sonification, with the first using distinct piano tones for data point navigation and the latter two employing continuous pitch changes to reflect y-axis variations in math functions. Additionally, past research has developed sonification methods for representing line charts, where pitch variation reflects changes in the y-axis values and time or manual navigation corresponds to movement along the x-axis within a selected line [336, 162, 218, 286, 14]. Such solutions allowed users to follow the progression of data points through a continuous auditory experience, distinguishing quadrants and identifying discontinuity points. However, relying solely on sonification falls short of providing a comprehensive understanding, as users with BVI need more intuitive ways to understand and interpret the spatial arrangement of 2D data [199]. Additionally, the ability of these interfaces to summarize information or represent key data points has only been studied with simple line charts containing no more than five lines and few intersections.

Multimodal Speech-Sonification

More advanced audio-driven user interfaces have employed both speech and sonification approaches to assist BVI individuals in learning and interacting with digital line charts. This includes combining pitch-y-mapping sonification with data-insights speech descriptions [295] or with overlayed POI speech-based earcons to improve understanding of math functions [14]. Aiming to support trend and line comparison, past research has also employed overlaid POI speech-based earcons with stereo-panned MIDI-based virtual instrument tones assigned to each line [139]. While audio-driven multimodal approaches offer significant scalability, BVI individuals underscore that tactile and haptic feedback are essential for comprehending and interpreting the spatial arrangement of 2D data [199].

Tactile Graphics

Tactile representations and drawings, such as Braille-embossed and swell paper, are widely used in the BVI community for effectively communicating graphic shapes and learning 2D data, including line charts [157]. Past literature has investigated substantially tactile formats and guidelines to make line charts easier to interact with and explore [96, 99, 97, 18]. However, despite their advantages, tactile representations are limited in conveying detailed graphical information, especially for dynamic and complex representations [19, 195]. This holds true for line graphs, as complex line charts with numerous intersections and convergences cannot be effectively represented in a single tactile graphic and often require multi-page representations, which hinders the ability to compare trends and lines [213].

Multimodal audio-haptic interface

A practical approach to supporting BVI individuals in learning dynamic 2D graphs and understanding spatial arrangements is integrating audio with haptic feedback, commonly realised through tap-to-hear exploration (also known as point-to-click interaction) [310]. This multimodal interaction allows users to explore tactile graphics by moving their hands across the surface and querying specific elements through fingertip detection or touch, receiving pinpointed audio descriptions to access the line chart data. Tap-to-hear exploration has been extensively studied and employed in tactile graphic readers to assess how effectively users with BVI can learn and interpret line and data charts [194, 110, 52, 94]. Additionally, some studies have implemented such exploration using digital pen (stylus) interactions to query the pinpointed audio descriptions [310, 93]. To avoid overwhelming users with lengthy audio descriptions, some approaches have implemented additional tap motions to divide the information into multiple levels, thus overcoming this challenge [202, 197, 195, 196, 93].

Other approaches have explored alternatives to tap-to-hear by implementing audio-haptic finger-slide interactions to support the learning of line chart shapes, either through sonification pitch changes on touch screens [286, 14] or 1-DOF slide and tilt-tone feedback [103]. While showing promising results for providing a quick overview of a line, users can only perceive one line at a time, making it more challenging to compare trends and identify intersection points.

More advanced user interfaces have progressed by augmenting the baseline standard tap-to-hear interaction with additional interaction features. This includes the ability to select and explore each line individually, with audio feedback reflecting the projected x-axis position (pitch varying with the y-value) and vibration feedback upon contact with the visual line [336]. 2D refreshable tactile pin display-based solutions have also augmented the tap-to-hear exploration with zooming and filtering line capability to improve access and interpretation of SVG-PDF-based line charts [203, 168, 265, 207, 17].

Despite the significant number of approaches developed thus far, a standardised, effective solution for exploring line charts in 2D tactile graphic readers has yet to be established. Audio-tactile tap-to-hear graphic exploration has emerged as a promising solution for addressing this challenge, as it has proven effective in several graphic learning challenge domains. Nevertheless, past literature has focused on straightforward line charts, neglecting to validate solutions with realistic, complex charts featuring numerous intersections and convergences. This research gap highlights the need for further investigation into how these advanced multimodal interactions can be adapted to support users in learning and interpreting all types of line charts.

5.1.2. UI Design: Line Chart Exploration

This dissertation investigates three distinct audio-tactile user interfaces for assisting BVI individuals in learning and exploring tactile line charts: Tap-to-Hear Graphic Exploration (state-of-the-art), Trigger Line Tracing Exploration (proposed), and Melodic Line Tracing Exploration (proposed). All UIs were developed on Java and implemented on the Tactonom Reader device. The two proposed user interfaces (Trigger and Melodic Line Tracing) utilized real-time audio processing, incorporating variations in volume, pitch, and audio sources, using MINIM version 2.2.2 [85] and OpenAL (LWJGL) version 3.3.3 [84], respectively. To ensure scalability and compatibility with various screen sizes, the proposed algorithms were designed using a standardized 100×100 digital coordinate system, mapping audio listeners accordingly.

Tap-to-Hear Graphic Exploration UI

Building on past literature [194, 110, 52, 94], a standard SVG-based tap-to-hear graphic exploration user interface was designed and implemented on the Tactonom Reader (Figure 5.2). Users explore SVG tactile graphics by using one hand to pinpoint elements (cursor hand) and the other to query the associated audio information by tapping the "query-info" button. Associated information is determined by the SVG element's "title" attribute, which can contain a string for text-to-speech (TTS) output or an OPUS file for audio playback. When the hand cursor overlaps multiple SVG elements, the system prioritizes and plays the information associated with the topmost layer of the SVG structure. If the cursor hand points to an empty area, a short "no-result" beep audio is played.

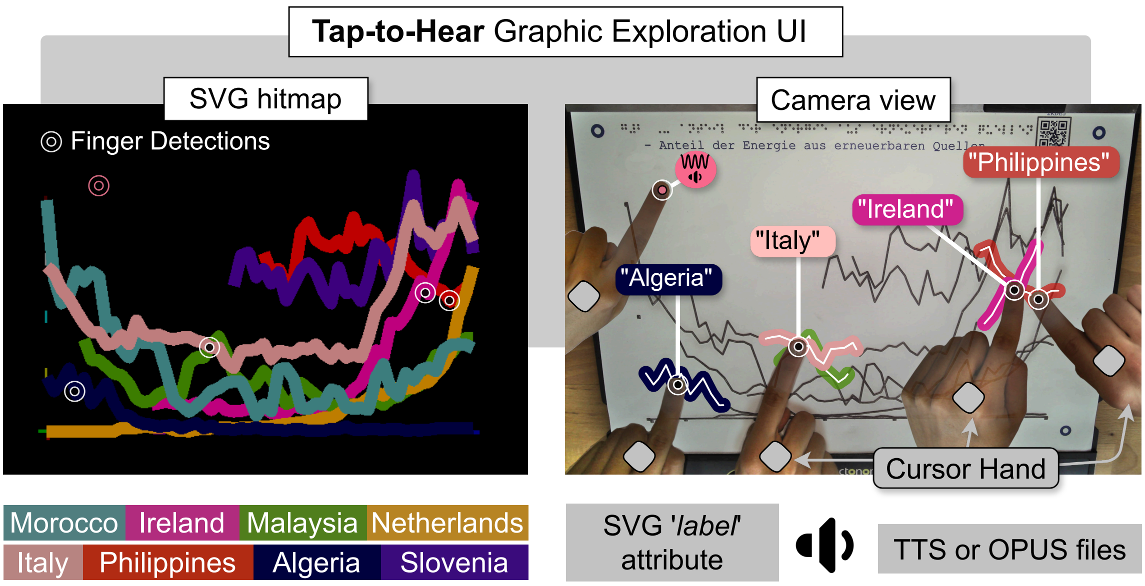

Figure 5.2.: Tap-to-Hear Graphic Exploration UI: Line Chart Context

Trigger Line Tracing UI

Drawing inspiration from advanced multimodal audio-haptic solutions from past literature and extending the standard tap-to-hear graphic exploration UI, a dynamic trigger-based line-tracing UI was designed and implemented on the Tactonom Reader (Figure 5.3). This solution introduces dynamic interaction through real-time fingertip tracking and adaptive audio processing, operating across two states: trigger intersection and line tracing.

When a line chart is opened, the trigger intersection state is activated. In this state, users move their cursor hand to locate a line. Upon first contact with a line, a 0.5-second trigger sound is played. As users follow the line and reach an intersection with a new line, the trigger sound is played again. If they move away from the line and later touch it again, the sound is replayed. The system tracks the last interacted line and only triggers the sound when a new line is detected. If users move into a space without lines, the last tracked line is reset. This approach aimed to provide feedback on intersections without overwhelming the user with excessive auditory cues.

Upon locating a line, the user can press a tactile button to access additional line details, thereby activating the line-tracing state and muting trigger intersection feedback. Inspired by previous research on pitch-y-mapping sonification [336, 162, 218, 286, 14], this state plays a continuous 0.5-second beep trace sound, with its playback speed (rate) linearly adjusted based on the user's cursor hand's y position. The playback speed ranges from 1.0× to 3.0×, mapped to the device's bottom and top y positions. The beep loops as long as the user follows the selected line, ceasing when the cursor moves away and restarting when the line is re-engaged. Pressing the tactile button once again deselects the line, returning the system to the trigger intersection state.

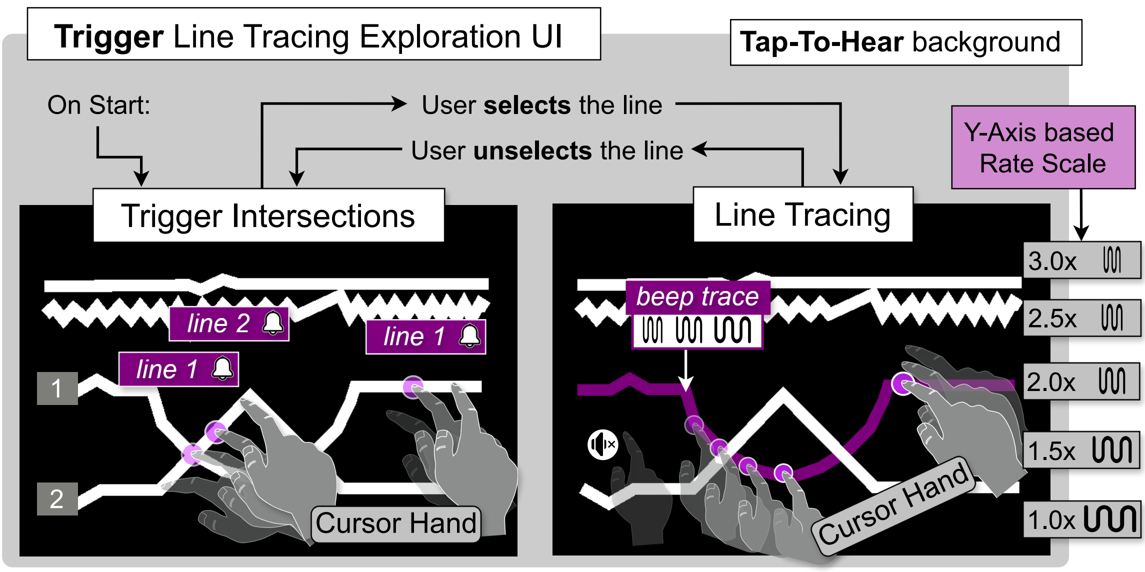

Figure 5.3.: Trigger Line Tracing Exploration UI. Augments Tap-to-Hear Exploration with two features.

Melodic Line Tracing UI

Following a human-centred design methodology and building on insights from Section 5.2, the Melodic Line Tracing Exploration UI is proposed—an enhanced, dynamic interface designed to improve upon the Trigger Line Tracing UI (Figure 5.4). Like its predecessor, it extends the Tap-to-Hear Exploration UI by incorporating real-time fingertip tracking and adaptive audio processing. However, this iteration specifically addresses previous limitations by refining intersection feedback for multi-line trend comparison and improving the line-tracing algorithm. The UI operates across two states: a multi-line state for broader exploration and a line-focus state for detailed tracing. Its design introduces three key features: a synth melody environment for multi-line awareness, pitch-based trace guidance for following individual lines, and line boundary feedback to enhance line tracing. Similar to its predecessor, one tactile button is dedicated to tap-to-hear exploration, while another is used to select and deselect lines.

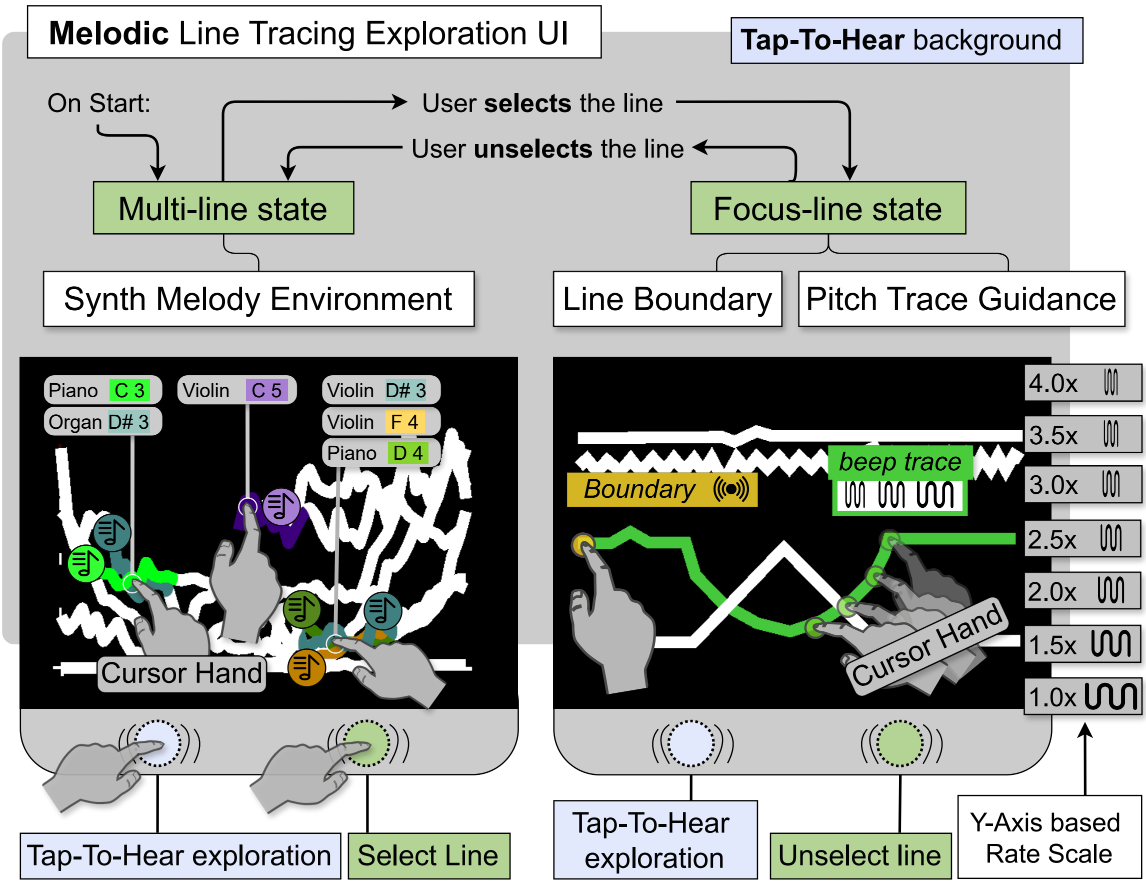

Figure 5.4.: Melodic Line Tracing Exploration UI: An improvement on the Trigger Line Tracing UI, extending Tap-to-Hear UI with three features: synth melody environment, pitch trace guidance, and line boundary.

When an SVG line chart is opened, the system enters the multi-line state, activating the **synth melody environment** (Figure 5.5). At the start, digital synthesizers are cyclically assigned to the chart's lines. In total, four synthesizers were used, each emulating a different musical instrument: piano(s1), organ(s2), violin(s3), and trombone(s4). If the number of lines exceeds four, the assignment repeats in sequence (e.g., s1, s2, s3, s4, s1, s2, …) to ensure consistent auditory representation across all lines. All synthesized sounds are 4.0-second loopable audio OPUS files at a baseline frequency of C4 (261.63 Hz, MIDI note 60) with a playback rate of 1.0. To further distinguish each line, the synthesized sounds are mapped to a fixed melody, designed with input from blind audio engineers using a human-centred design methodology. The melody, consisting of the notes (C, D#, G, A#, D, F, A, C, repeated), was chosen to maintain harmonic coherence while ensuring that each tone is easily distinguishable. If the number of lines exceeds seven, the starting frequency melody assignment is shifted from C4 (261.63 Hz -4th octave) to C3 (130.81 Hz -3rd octave) to prevent excessively high-pitched tones.

Contact with a line triggers the continuous playback (loop) of its corresponding synthesized sound along with its assigned melody note. As the user's finger moves toward an intersection, the synthesized sounds of the intersecting lines play simultaneously, even when assigned the same synthesized instrument, as their melody notes remain distinct. In complex cases with four or more overlapping lines, all overlapping synthesized sounds are played simultaneously. If the user's hand moves away from the lines, sound playback stops. A subtle background sound is present during multi-line exploration to differentiate the multi-line state from the focus-line state. This auditory cue provides feedback on the active state without interfering with the perception of the individual line sounds, ensuring users can focus on their interaction.

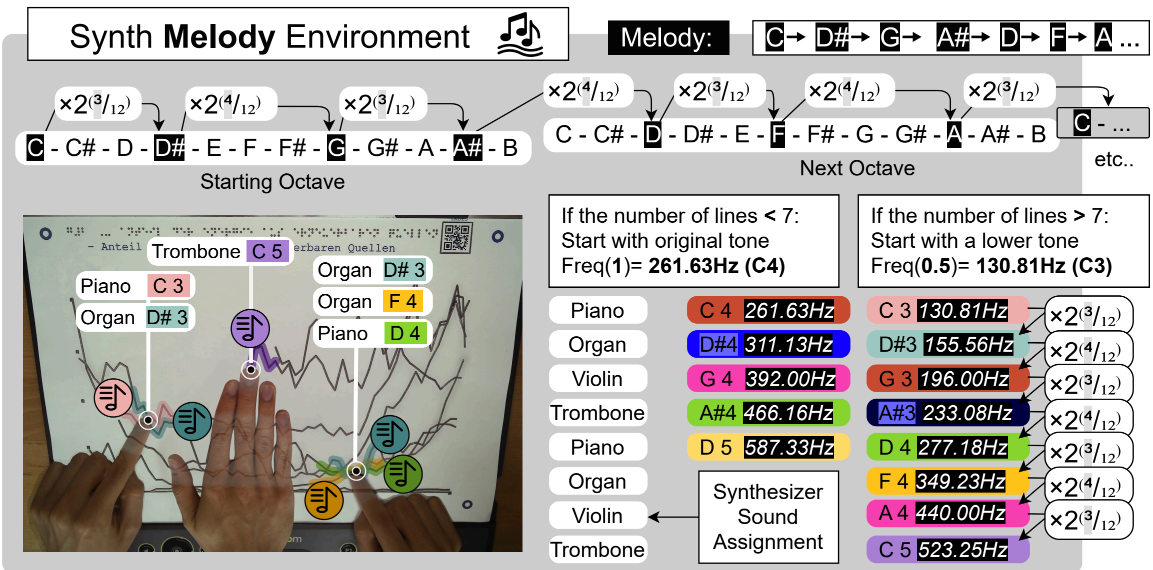

Figure 5.5.: Melodic Line Tracing Exploration UI: Synth Melody Environment Overview

Beyond comparing multiple trends, users can focus on a specific line by placing their finger on it and pressing the **focus-line activation** button (Figure 5.6). Upon activation, a brief beep crescendo plays, followed by the line's associated SVG title. Deactivation occurs when the user presses the same button while selecting either the same line or a blank space, triggering a brief beep decrescendo. If the user's finger is at an intersection, the focus-line state will not activate. Instead, the system announces the names of all intersecting lines, allowing the user to select one through an arrow key menu. When the focus-line state is activated, the multi-line background sound is completely muted, and the synthesized environment is softened, preserving line intersection context while emphasizing the selected line.

Similar to its predecessor, this UI generates a continuous 0.5-second beep trace sound whose playback rate varies linearly with the user's cursor hand's y-position along the line. However, unlike the previous version, the playback speed now ranges from 1.0× to 4.0×, mapped to the device's bottom and top y-limits. Increasing the playback rate not only shortens the sound but also raises its pitch, reinforcing the perception of vertical movement along the line. The beep loops continuously as long as the user follows the selected line, stopping when the cursor moves away and resuming upon re-engagement. Additionally, line boundary feedback was integrated to help users identify the line's edges and extrema (start, end, maximum, minimum). A brief, overlapping gong-like percussion sound (contrasting with the synthesized sounds of keys, strings, and bass) plays when the user reaches either end of the line, marking its boundaries. When the user reaches the global maximum or minimum y-position of the line, the playback rate increases to 5.0× or decreases to 0.5×, providing a clear auditory cue for the line's vertical limits. This change is relative to the specific line, not the y-axis, accentuating the distinction between linear line tracing and the line's extremities.

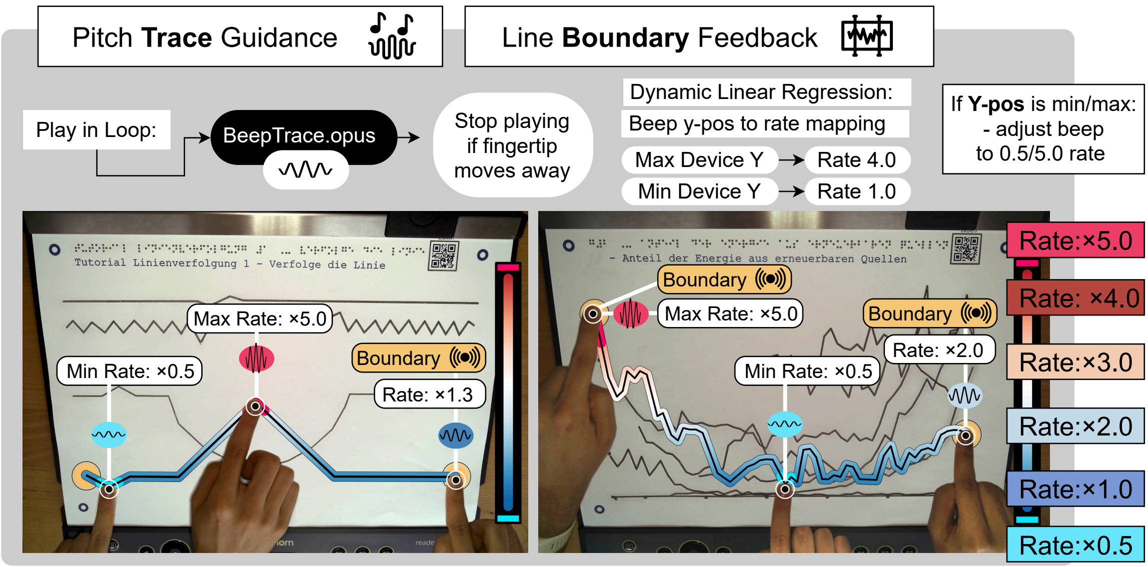

Figure 5.6.: Melodic Line Tracing Exploration UI: Pitch Trace Guidance and Line Boundary Feedback

5.2. EXPLORING THROUGH TRIGGER LINE TRACING

Due to the absence of a widely applicable and effective method for enabling BVI individuals to learn and explore line charts using tactile graphic readers, a preliminary user study was conducted to systematically evaluate the state-of-the-art tap-to-hear exploration approach in comparison to the proposed trigger-trace UI for line chart exploration. These user interfaces were implemented on the Tactonom Reader device and tested on A3-sized SVG-based audio-tactile line charts, ranging in complexity from incorporating two to nine lines. Beyond assessing efficiency and user satisfaction, the study aimed to determine whether these exploration techniques sufficiently support BVI users in understanding complex line charts specifically or if further advancements are required to address this challenge entirely. Additionally, the potential applicability of these UIs in broader contexts was explored.

Participants

Four BVI participants (one female, three males; Table 5.1) were recruited in Karlsruhe through the "Center for Digital Accessibility and Assistive Technology" of KIT (*ACCESS@KIT*). Individuals expressing interest received detailed study information and were eligible to participate if they reported a medical diagnosis of visual impairment or blindness, as visual acuity was not directly measured. Exclusion criteria included being under 18 years of age, substance abuse, and medical conditions affecting cognition, hearing, communication, touch, or motor skills. The study was approved by the Karlsruhe Institute of Technology ethics committee, and all participants provided informed consent. Based on self-reports, two participants were classified as congenitally blind (CB), while the remaining two were categorized as late blind (LB). All participants had prior experience with 2D graphic readers and 2D refreshable tactile pin displays. The limited sample size does not allow for extensive statistical analysis. However, such early-stage investigations play a crucial role in human-centred design by capturing initial user experiences and identifying usability challenges. These insights are essential for refining the user interface, guiding future iterations, and ensuring that subsequent research builds upon a solid foundation of user needs and real-world applicability.

Table 5.1.: Participant demographics (P1-P4).

Users	Gender	VI Type (VA)	Age Range
P1	male	CB (< 3/60)	28-37
P2	male	CB (< 3/60)	38-47
P3	male	LB (< 3/60)	18-27
P4	female	LB (< 3/60)	18-27

Visual acuity (VA) levels defined by the WHO [3].

Materials - Graphics

A total of seven mathematical line charts were used: one (a tutorial) for learning the exploration UIs and six for UI evaluation (Figure 5.7). All line charts were manually collected from scientific papers across diverse fields as PDF charts. Using easyOCR and window averaging algorithms, lines from PDFs were translated into SVG formats [239]. SVGs were then formatted in accordance with the open-source ProBlind database layout, aligning with the requirements of the Tactonom Reader [233]. Each *SVG* graphic includes a QR code in the top-right corner and four blue circle markers and was printed using an Everest-D V5 Braille embosser in A3 format. Tactile embossed paper was used instead of swell paper to extend the user interface outcomes not only to 2D tactile graphics readers but to 2D refreshable tactile pin displays. For Braille embossing, a pin spacing of 2.5 mm and a pin diameter of 1.3 mm were used, ensuring compatibility with most 2D refreshable tactile pin displays [237]. To support user learning, a straightforward tutorial line chart with two intersecting lines was provided. For evaluation, six distinct line charts were used, categorized by line count: 2-line (exercise), 3-line (charts 1 and 2), 6-line (charts 3 and 4), and 9-line (charts 5 and 6). Notably, "*Line Chart 6*" does not contain intersections but features a line positioned below another.

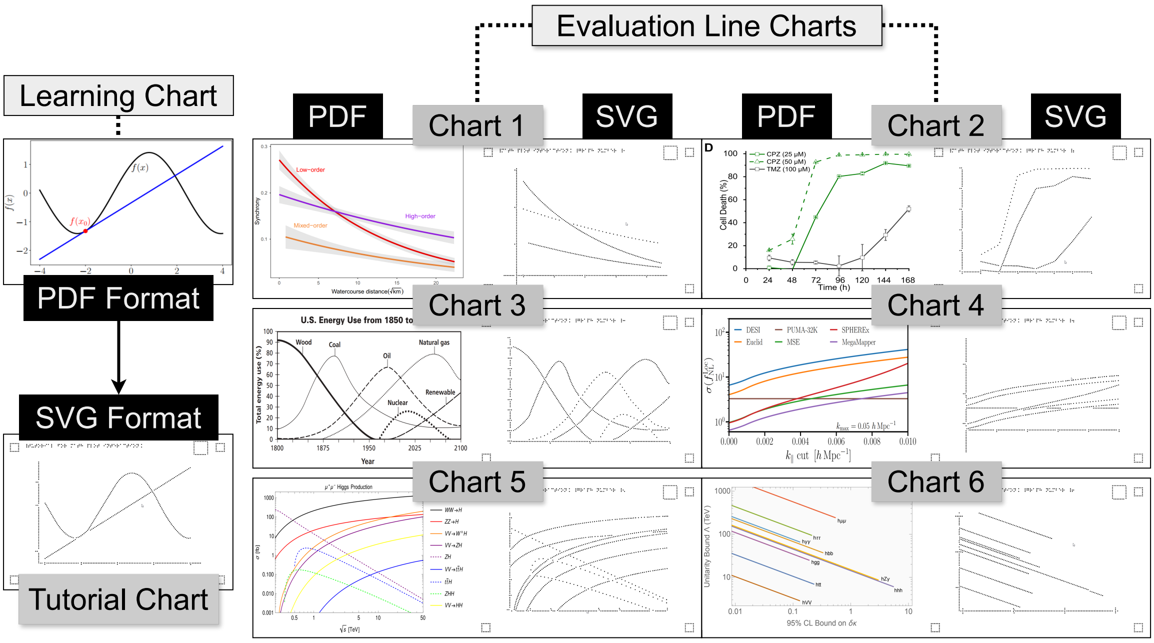

Figure 5.7.: Audio-Tactile line charts used in the study to aid participant learning (top) and to evaluate the exploration UIs (middle-bottom). The digital original PDF format and embossed paper SVG format are presented for comprehensive context.

5.2.1. Experimental Setup

A within-subjects design was employed, with each participant interacting with both user interfaces (trigger-trace line chart exploration and tap-to-hear graphic exploration). To control for order effects, a counterbalanced design was used, systematically varying the combinations of user interfaces and line chart sets (1st Set: 2, 3, 6; 2nd Set: 1, 4, 5). Given the two UIs and two sets, four unique order combinations were tested (UI1-Set1 → UI2-Set2, UI1-Set2 → UI2-Set1, UI2-Set1 → UI1-Set2, and UI2-Set2 → UI1-Set1). These were evenly distributed across the four participants, ensuring each order was assigned to one participant. This counterbalance aims to minimise biases from order effects and enhance the reliability of the comparative analysis. Each participant completed the study in a single 90-minute session. Additional task details are provided in the supplementary (see Appendix B.2). Figure 5.8 illustrates the step-by-step progression of the experimental procedure, providing a clear overview of its distinct phases.

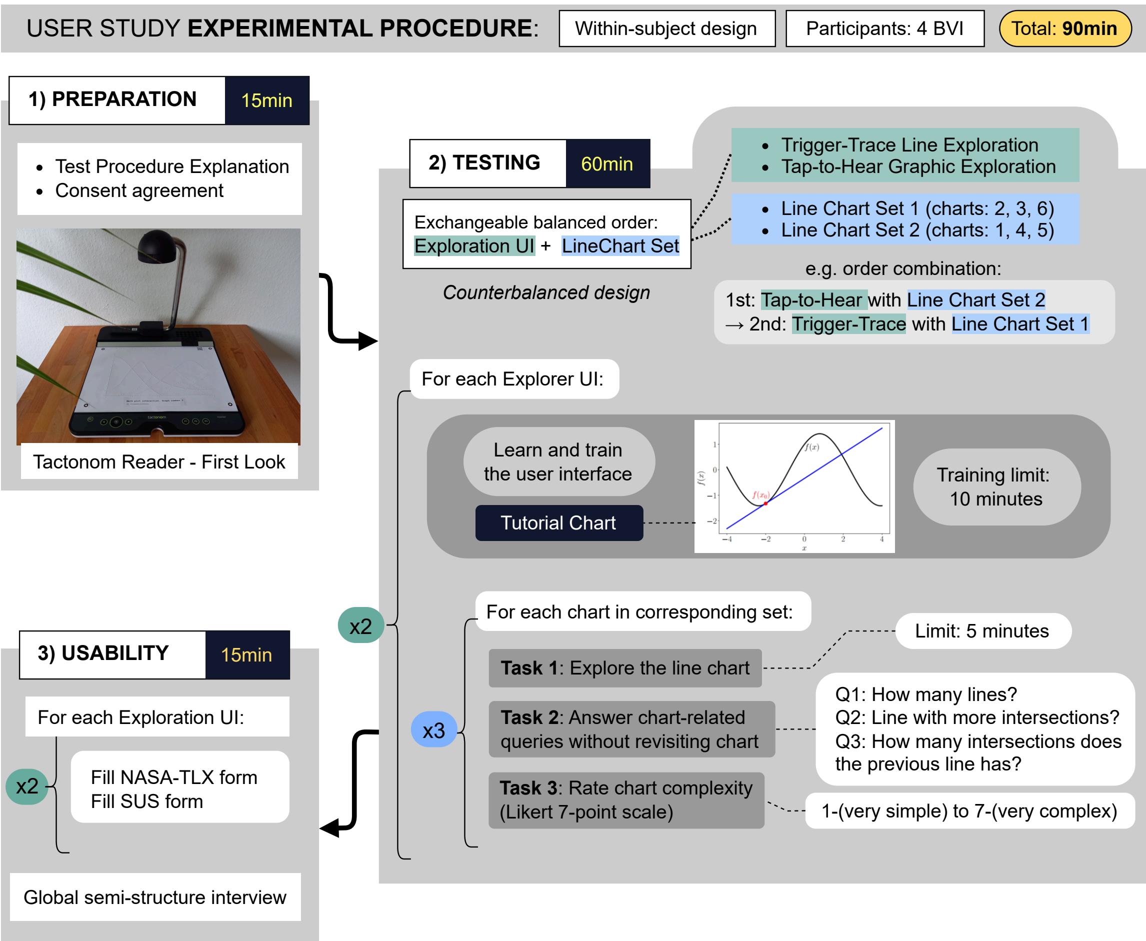

Figure 5.8.: Trigger and Trace Line Chart Exploration: Experimental Procedure

Study Procedure - Preparation

Upon arrival, participants were informed about the study and provided informed consent in their preferred format (digital, tactile paper, or audio). They then completed a ten-minute familiarization phase, during which they explored the Tactonom Reader using embossed paper graphics to acclimate to its dimensions and interaction workflow.

Study Procedure - Testing

Following the preparation phase, participants completed two testing sub-sessions, each dedicated to one of the user interfaces. Each sub-session began with a 10-minute familiarization period using the tutorial line chart. Participants then proceeded with their assigned line chart set, where embossed tactile line charts, increasing in complexity (3-line, 6-line, 9-line), were sequentially presented on the Tactonom Reader. A beep signalled when each chart was ready for interaction, after which participants had up to five minutes to explore it, with the option to conclude the exploration earlier if they confidently felt they had thoroughly examined the chart. Before exploring the subsequent chart, participants rated its complexity on a 7-point scale (1 = very simple, 7 = very complex) and answered three questions: (1) "How many lines does the graphic have?", (2) "Which line has the most intersections?" and (3) "How many intersections does this line have?".

Study Procedure - Usability

At the conclusion of the study, participants assessed each exploration user interface by answering the NASA-TLX [132] and SUS [23] questionnaires. Subsequently, they took part in a semi-structured interview to discuss their user experience, including their preferred interface and reasons for their choice, the perceived complexity of the tactile line charts, and potential applications of the UIs in other contexts.

Data Analysis Methodology

A mixed-methods approach was employed, integrating qualitative and quantitative data, including feedback from the semi-structured interviews. Analyses addressed efficiency (chart exploration duration), effectiveness (correct answer rate), and user satisfaction (normalized NASA-TLX and SUS scores). Descriptive statistics, including averages and standard deviations, were used to summarise the quantitative data. Subjective data from interviews were analysed using thematic analysis. Statistical analysis was not conducted. Participant feedback was labelled with unique identifiers and categorized by visual impairment type (CB: congenitally blind, VI: visually impaired, e.g., P2, CB).

5.2.2. Results

The study examined the efficiency, effectiveness, and user satisfaction of the two exploration UIs, focusing on their reliability in helping BVI individuals learn line charts. This included analysing different charts to assess whether these UIs remain effective not only for simple charts but also for realistic, complex line charts. Additionally, the study explored the potential scalability of tailored UIs for line chart exploration across various contexts.

Exploration UI Comparison

UI efficiency was assessed by measuring the total time participants took to explore each evaluation line chart (Figure 5.9, leftmost plot). The mean exploration time per chart was 159.0 ± 99.8 seconds for the tap-to-hear UI and 214.1 ± 100.2 seconds for the proposed trigger-trace UI. On seven occasions, participants used the full five-minute limit (300 seconds), with two instances occurring in the tap-to-hear UI and five in the trigger-trace UI. UI effectiveness was evaluated based on the distribution of correct responses per chart (Figure 5.9, left-centre plot). The mean number of correct answers per chart was 2.33 ± 0.98 for the tap-to-hear UI and 2.08 ± 1.17 for the trigger-trace UI, indicating lower accuracy with the latter despite the increased exploration time.

User satisfaction was compared using normalised (0–100) SUS and NASA-TLX scores (Figure 5.9, right-centre and rightmost plots). The mean SUS score was 90.0 ± 7.4 for the tap-to-hear UI and 88.1 ± 10.9 for the trigger-trace UI, suggesting higher user satisfaction with the former but indicating a good level of satisfaction based on previous research [23]. For NASA-TLX, the mean score was 23.3 ± 6.0 for the tap-to-hear UI and 28.3 ± 3.53 for the trigger-trace UI, indicating a lower perceived workload for the tap-to-hear UI.

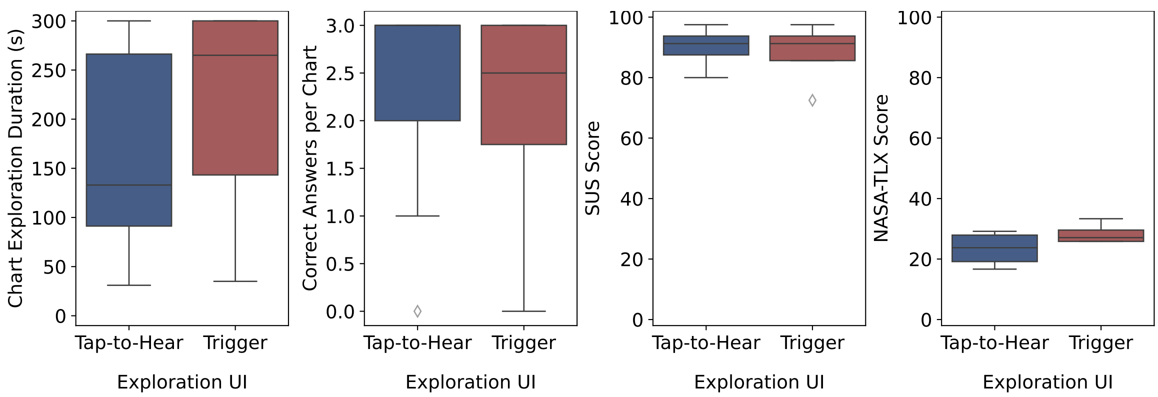

Figure 5.9.: UI Comparison Analysis. The leftmost plot depicts the time (in seconds) users spent exploring each line chart. The left-centre plot shows the distribution of correct answers per chart. The right-centre plot displays participants' normalized SUS scores, while the rightmost shows their NASA-TLX scores.

In the semi-structured interviews, participants were asked about the usefulness of the two user interfaces in uncovering more details in line charts. While previous results showed that participants completed the task more quickly and with less perceived workload using the tap-to-hear UI, all participants agreed that they could access more detailed information with the trigger-trace UI: "I could find more detailed information!" – (P1, CB), "It was easier to follow the lines. If there are a lot of lines, I know better where the line is going." – (P2, CB), "It is very helpful and accurate, and I was able to detect one line on top of another." – (P4, LB).

Line Charts Comparison

In addition to the UI-level comparisons, individual line charts were analysed by comparing exploration times and participant complexity rates (Figure 5.10). Evaluation charts 1 and 2 had the lowest mean exploration durations (97.50 ± 72.89 s and 74.24 ± 33.35 s, respectively) and the lowest mean user complexity rates (1.75 ± 0.50 and 1.75 ± 0.96, respectively). Charts 3 and 4 had mean exploration durations of 285.00 ± 17.32 s and 223.75 ± 88.26 s, respectively, and mean user complexity rates of 5.25 ± 0.50 and 4.75 ± 0.96, respectively. Chart 5 had the highest mean exploration duration (291.25 ± 6.50 s) and the highest average user complexity rate (6.50 ± 1.00). Although Chart 6 also contains nine lines, its average exploration time of 147.50 ± 75.89 s was nearly half that of Chart 5, and its average user complexity rate of 2.00 ± 0.00 was substantially lower.

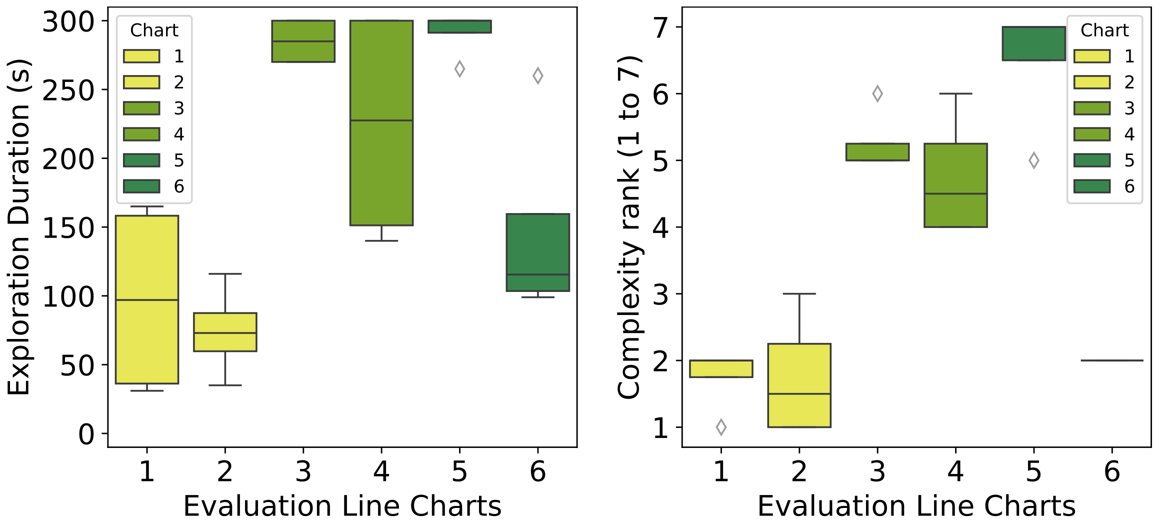

Figure 5.10.: Line Charts Analysis - Efficiency and Rank. Distribution of users' exploration durations for each line chart (left plot) and the distribution of complexity ratings per chart (right plot).

The distribution of correct answers per line chart, grouped by question, was also analysed (Figure 5.11). Participants answered all three questions correctly for Graphics 1 and 2. Graphic 6 had by far the highest number of incorrect responses, with only 2 correct answers out of 12. This is particularly notable considering that Graphic 6 exhibited the third-lowest average exploration time and complexity rate. One possible explanation is that Graphic 6 features two overlapping lines, rendered as one line, due to the limited resolution of the Braille embossed paper (the lines were too closely spaced in the PDF). The bottom line is only accessible through pinpoint interaction at the lower edge, where the top line ends. This critical detail went unnoticed by most users (3 out of 4), which contributed to the lower number of correct answers.

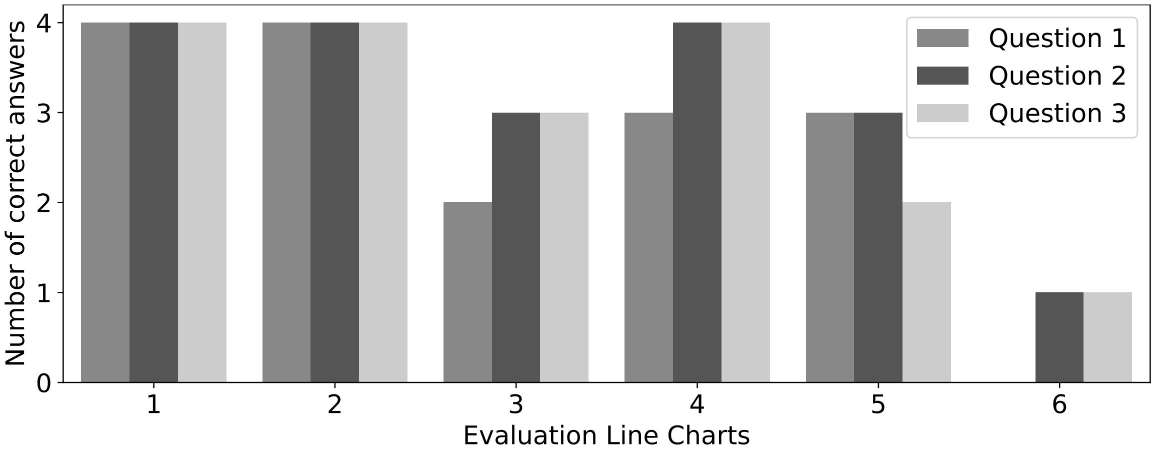

Figure 5.11.: Line Charts Analysis - Effectiveness. Correct answers per line chart, grouped by question.

UI Improvements and Applicability

Participants identified key challenges with complex line charts and offered valuable insights into improving the trigger-trace UI to address these challenges. Three out of four participants highlighted the challenge when two lines overlap, as seen in evaluation chart 6: "It would be helpful if the system could tell me when I am on a line that has another line under it" – (P4, LB). Proposed improvements included playing additional tracing tones and better intersection recognition: "Recognise where an intersection is, instead of recognising if there is a new line." – (P3, LB), "It should trigger when you cross the X and Y axis as well, not just when crossing a new line." – (P2, CB).

During semi-structured interviews, participants were also asked about other contexts in which a tailored line chart exploration UI could be useful: "A lot of topics in school and university. Astronomy maps as well!" – (P1, CB), "Mathematics and physics, including electric circuits." – (P2, CB), "Mathematics and physics, including electric circuits." – (P3, LB), and "Analysis of trends in data." – (P4, LB). These suggestions indicate that an improved trigger-trace UI could assist individuals with BVI in perceiving and understanding 2D data across various contexts beyond line charts.

5.2.3. Discussion

Low Performance of Trigger-Trace

The standard tap-to-hear UI outperformed the proposed trigger-trace UI with faster exploration times and higher effectiveness on the evaluation line charts. In contrast, the trigger-trace UI—despite offering additional details on shapes and intersections—resulted in longer task durations and a higher perceived workload. Notably, these extra features of the trigger-trace UI did not improve accuracy, and participants provided fewer correct responses even with the extended exploration time. While participants recognised the trigger-trace UI's potential to provide more detailed information and its usefulness in other 2D data contexts, it still falls short in effectively addressing all line charts. Key issues included the inability to determine the start and end boundaries of each line and the lack of an intuitive way for recognising intersections.

These findings highlight that tailored features can increase task duration and cognitive load without improving performance, emphasising the importance of iterative user testing and human-centred design. While the trigger-trace UI showed promise in some aspects, further refinement is essential to better balance feature complexity with usability and performance in line chart exploration. As participants underscored, developing such a UI is critical not only for overcoming the accessibility challenges inherent in line chart exploration but also for empowering BVI individuals to navigate a broad spectrum of 2D data, opening new possibilities for data interpretation across diverse contexts.

Fully Addressing Complex Line Charts

Results indicate that standard tap-to-hear and trigger-trace exploration UIs are effective for helping BVI individuals understand straightforward line charts but fall short when addressing more complex charts. Although some charts were perceived as relatively easy with short exploration times, they resulted in a low number of correct answers, as participants overlooked some details, such as overlapping lines. There is a clear need for an advanced solution capable of comprehensively addressing the inherent complexities across all line chart types, enabling BVI individuals not only to perceive explicit data but also discern nuanced and concealed information critical for accurate interpretation.

Furthermore, a more robust evaluation methodology is essential to assess UI effectiveness comprehensively. This should encompass not only participants' ability to navigate the chart's lines and identify intersections but also their capacity to discern relationships between lines, thereby ensuring a deeper understanding of the data being conveyed. In other words, the analysis should evaluate whether users can not only explore the chart but also extract meaningful insights from the data, which is the primary purpose of line chart representations. Such a methodology is indispensable to guarantee the development of a UI solution that genuinely facilitates line chart comprehension.

5.3. EXPLORING THROUGH MELODIC LINE TRACING

Building on the findings from the preliminary study (section 5.2) and adhering to the human-centred design methodology central to this dissertation, a second, more extensive user study was conducted to investigate the proposed Melodic Line Tracing Exploration UI. Implemented on the Tactonom Reader, the proposed UI (excluding tap-to-hear) was compared against the Tap-to-Hear Graphic Exploration UI, with a focus on assessing effectiveness, efficiency, and user satisfaction for learning and exploring realistic, complex tactile line charts. Beyond aiming to outperform the state-of-the-art approach, the study aimed to determine whether the proposed UI could fully address the challenge of enabling BVI individuals to learn and explore real-world line charts effectively and efficiently. In alignment with the broader objectives of this dissertation, the study also investigated the impact of line chart complexity and the scalability of the UI across different domains.

Participants

Ten BVI participants (one female, nine males; Table 5.2) were recruited through the "Center for Digital Accessibility and Assistive Technology" of KIT (*ACCESS@KIT*) and the Nuremberg Educational Centre for the Blind and Visually Impaired (BBS-Nuremberg). Participants were eligible if they reported a medical diagnosis of visual impairment or blindness, as visual acuity was not directly measured. Exclusion criteria included being under 18, substance abuse and medical conditions affecting cognition, hearing, communication, touch, or motor skills. The study was approved by the Karlsruhe Institute of Technology ethics committee, and informed consent was obtained. Based on self-reports, six participants were classified as congenitally blind (CB) and four as visually impaired (VI). Participants' prior experiences with tactile graphics and 2D user interfaces were also collected.

Table 5.2.: Participant demographics and experience with 2D user interfaces (P1-P10).

Users	Age	Gender	VI Type (VA)	Graphics Exp.	2D UI Exp.
P1	18-45	male	CB (< 3/60)	yes	TPAD
P2	45-60	male	CB (< 3/60)	yes	TPAD, HyperBraille, IVEO
P3	18-45	male	VI (< 6/60)	yes	-
P4	18-45	male	VI (< 6/60)	yes	-
P5	18-45	male	VI (< 6/60)	-	-
P6	18-45	male	CB (< 3/60)	yes	-
P7	18-45	male	CB (< 3/60)	-	-
P8	18-45	male	CB (< 3/60)	yes	-
P9	18-45	female	VI (< 6/60)	yes	-
P10	18-45	male	CB (< 3/60)	yes	-

Visual acuity (VA) levels defined by the WHO [3].

Materials - Graphics

This study employed a total of six audio-tactile line charts: two for learning the exploration UIs and four for testing them (Figure 5.12). These graphics were formatted in accordance with the open-source ProBlind database layout, which aligns with the requirements of the Tactonom Reader [233]. This layout includes the QR code for graphic identification and four blue circles at each corner for mapping associated audio information in an SVG document (Swell paper format - SVG). Each line in the SVG format was rendered in black and filled with a stroke width of 1.3 mm. In the digital audio format, colours define a hitmap, with each colour representing a different audio element, randomly assigned for variety. For instance, the grey-coloured top line in "*Line Chart 1*" corresponds to the audio 'Brazil'. The coloured lines are enlarged to create larger targets (stroke width of 12.0 mm), facilitating accessibility for fingertip interaction. All graphics were printed on swell paper using a laser printer and subsequently processed through the PIAF (*Tactile Image Maker*) technology heating chamber [223].

To facilitate user comprehension and learning of the exploration UIs, two original graphics using Inkscape [234] were designed and uploaded to the ProBlind database [233] (Figure 5.12). Each graphic includes versions in both English and German, ensuring accessibility for users across different language backgrounds. "*Tutorial Chart 1*" comprises four lines: two lines at the top exhibit distinct shapes, with one relatively straight and the other featuring a zigzag pattern, while the bottom two lines showcase prominent peaks, troughs, and intersections. "*Tutorial Chart 2*" compromises five lines: two at the top and three at the bottom. The lines intersect and overlap, and not all fully extend from left to right, with certain lines appearing later and in the middle. Beyond facilitating learning of the exploration UI, these two graphics aim to offer users context regarding the situations they will encounter in the testing charts.

For evaluating the exploration UIs, four complex line charts sourced from *Renewable Energy - Our World in Data* [248] were re-adapted and uploaded to the ProBlind database [233] (Figure 5.12). These represent the distribution of primary energy consumption from renewable sources (Line charts 1 and 3) and the share of electricity production derived from hydropower (Line charts 2 and 4). Each line corresponds to the share of renewable energy or hydropower production for a different country over the past years. To prevent bias, shares were presented instead of absolute values, ensuring that users approached the tests without preconceived notions about the energy consumption of specific countries. Each graphic comprises eight lines, which, though seemingly straightforward for sighted individuals, are incredibly challenging to access and can cause confusion and frustration for people with BVI [239]. In essence, the testing line charts not only engage individuals with BVI by depicting real-world data but also effectively showcase the diverse challenges encountered when accessing line chart data. Featuring complexity with multiple intersections, overlaps, and lines that do not extend entirely from left to right, these charts demonstrate the inherent difficulties in navigating such graphical representations. Therefore, they serve as ideal testbeds for evaluating UI designs aimed at overcoming these challenges.

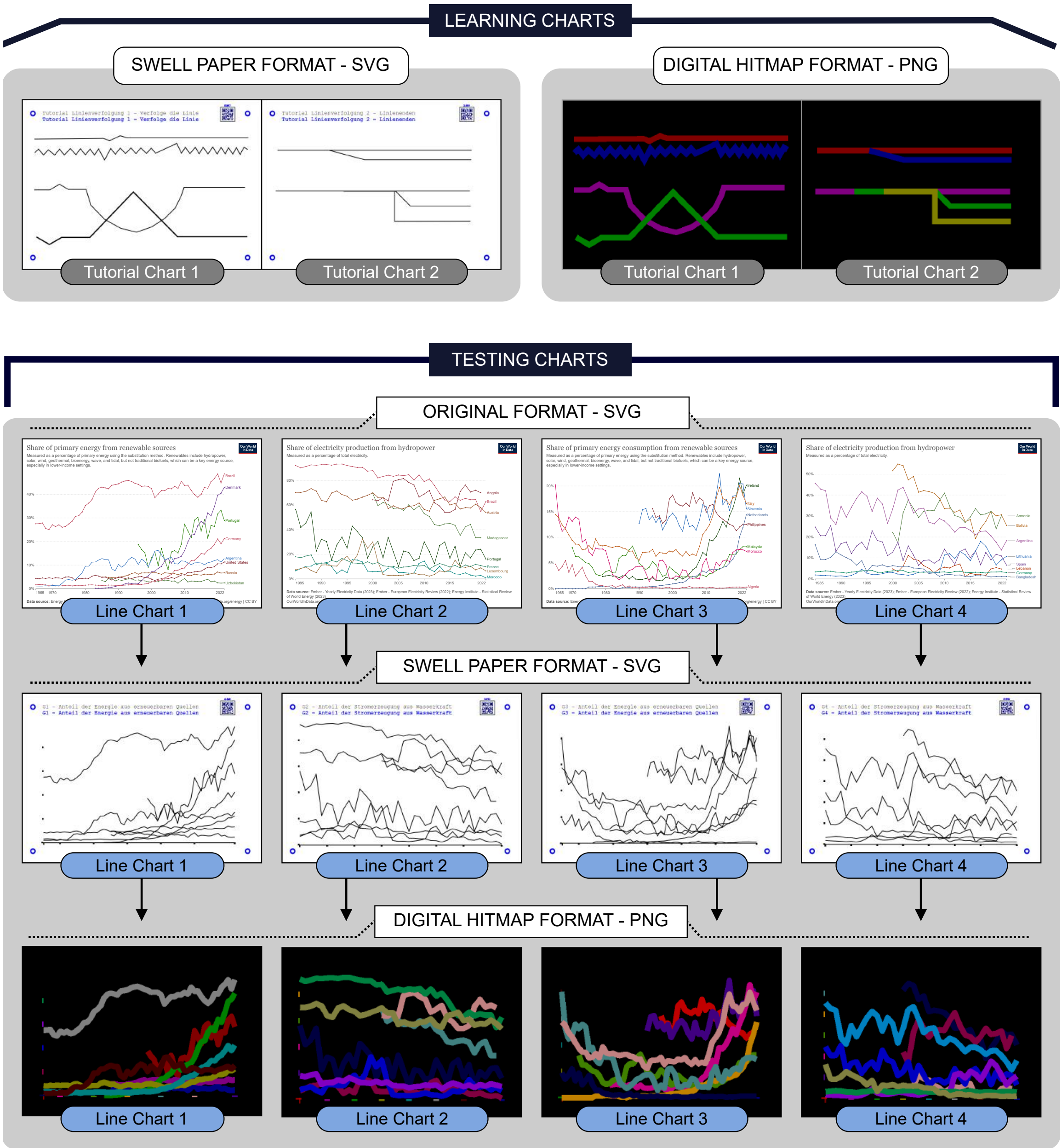

Figure 5.12.: Audio-Tactile line charts used in the study to aid participant learning (top) and to evaluate the exploration UIs (middle-bottom). The swell paper format (SVG) and the digital hitmap format (PNG) are presented for comprehensive context. In the digital hitmap format, different colours represent various audio elements that users can interact with. The colour choices for audio elements are randomised. The evaluation line charts are re-adapted and sourced from *Renewable Energy - Our World in Data* [248] and are available at the ProBlind database [233].

No participants reported prior knowledge or assumptions about the energy shares of specific countries or their relationships with others, ensuring that the analysis was unbiased and results based solely on the presented data.

5.3.1. Experimental Setup

A within-subjects design was utilised, allowing each participant to engage with both user interfaces Melodic Line Tracing Exploration and Tap-to-Hear Graphic Exploration). To mitigate order effects, a counterbalanced design was implemented, systematically varying the sequence of user interfaces and line chart sets (1st Set: 1 and 2; 2nd Set: 3 and 4). With two UIs and two sets, four distinct order combinations were established (UI1-Set1 → UI2-Set2, UI1-Set2 → UI2-Set1, UI2-Set1 → UI1-Set2, and UI2-Set2 → UI1-Set1). These combinations were evenly distributed among the ten participants, ensuring each order was assigned to at least two individuals. This counterbalancing approach reduced potential biases from order effects and reinforced the validity of the comparative analysis. Each participant completed the study in a single 90-minute session. Additional task details are provided in the supplementary materials (see Appendix B.2). Figure 5.13 presents a detailed visualisation of the experimental procedure, clarifying its distinct phases. While the Melodic UI incorporates Tap-to-Hear exploration, this was deactivated to isolate interaction methods and ensure a fair, distinct comparison.

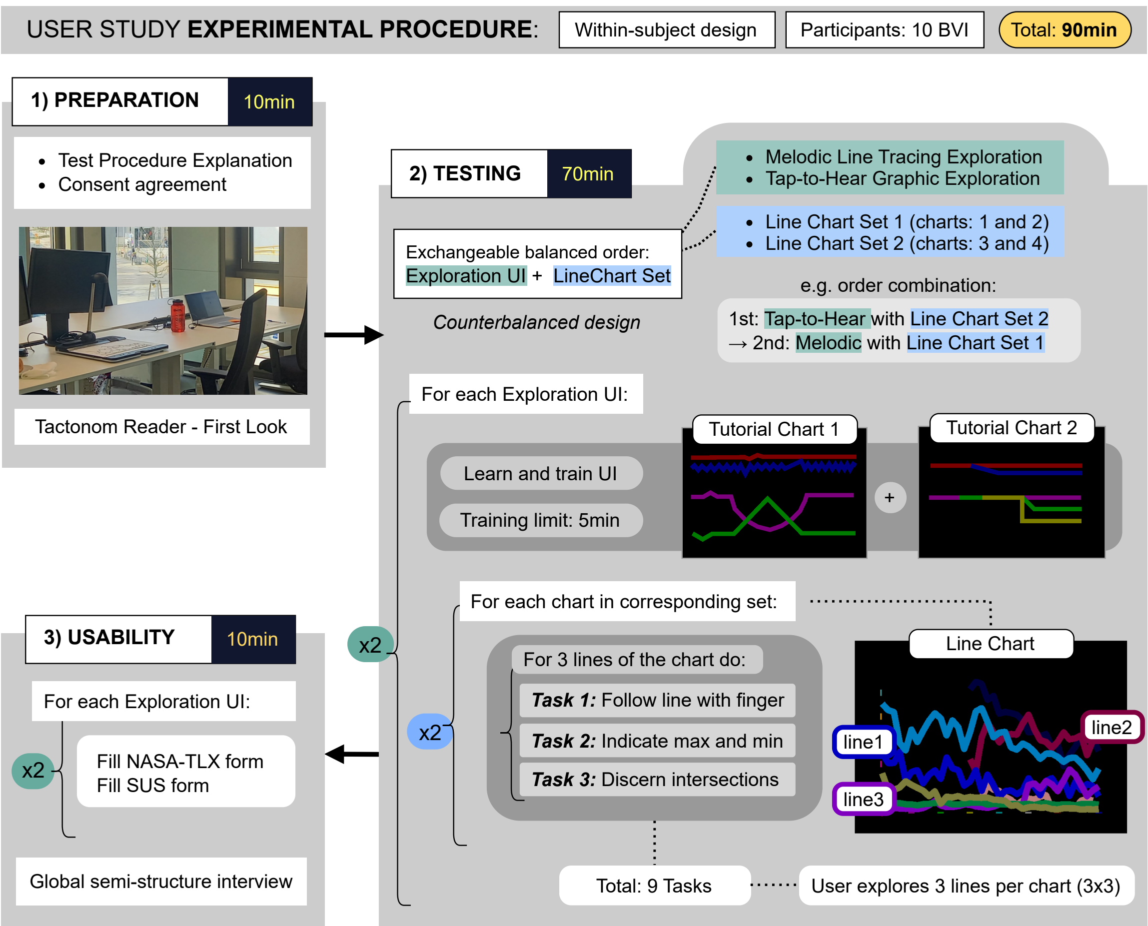

Figure 5.13.: Melodic Line Tracing Exploration: Experimental Procedure

Study Procedure - Preparation

At the beginning of the study, participants were introduced to the study and provided informed consent in their preferred format (digital, tactile paper, or audio). They then familiarised themselves with the Tactonom Reader, adjusting to its dimensions, creating a mental image of the device, and understanding the workflow, including placing tactile graphics and accessing audio through fingertip detection.

Study Procedure - Testing

Once familiar with the Tactonom Reader, participants moved on to the testing phase, which was divided into two matching sub-sessions, each focusing on one of the exploration UIs. For each sub-session, participants underwent a 5-minute familiarisation period to learn the functionality of the UI using two tutorial line charts. After learning, participants engaged in a 30-minute UI testing session, during which they performed tasks and answered questions about two assigned complex line charts. These tasks included tracing a line from one edge to another (Type 1), identifying its highest peak and lowest trough (Type 2), and determining the number of distinct intersections with other lines (Type 3). Participants performed each of these tasks on three pre-selected lines within the same chart. In total, participants attempted 18 tasks per exploration UI (9 Tasks per line graph). The tasks were always given in the same sequence for all participants.

Study Procedure - Usability

Following the study, participants provided feedback on each exploration user interface by completing the NASA-TLX [132] and SUS [23] questionnaires. They then participated in a semi-structured interview to reflect on their experience, discussing their preferred interface and reasons for their choice, the perceived complexity of the tactile line charts, and potential applications of the UIs in other contexts.

Data Analysis Methodology

A mixed-methods approach combined qualitative and quantitative data, including insights from semi-structured interviews. The analysis focused on efficiency (task completion time and normalised NASA-TLX scores), effectiveness (tasks correctly completed), and user satisfaction (normalised SUS scores), with these measures serving as the dependent variables. For statistical analysis, two-tailed Wilcoxon signed-rank tests were conducted to compare paired samples, while Friedman tests assessed differences across the four line charts. Descriptive statistics, such as means and standard deviations, summarised the quantitative data, while subjective feedback from interviews was examined using thematic analysis. Participant responses were labelled with unique identifiers and grouped by visual impairment type (CB: congenitally blind, VI: visually impaired; e.g., P6, CB).

5.3.2. Results

The study examined the effectiveness, efficiency, and user satisfaction of the two exploration UIs, focusing on their reliability in helping BVI individuals learn and interpret complex line charts. Additionally, the analysis investigated line charts' complexities and explored the Melodic tracing UI's main features and potential scalability. Figures in this section use specific markers and outliers to clarify the data. In the boxplots, the black markers represent the medians of visual impairment types: circles for CB (Congenitally Blind) and stars for VI (Visually Impaired). Outliers are marked as grey diamonds.

UI Effectiveness Analysis

Effectiveness was assessed by examining the number of tasks completed successfully per UI from two perspectives (Figure 5.14): first, considering each participant-line chart pair separately (20 samples per UI), and second, aggregating results per participant across all assigned charts (10 samples per UI). The mean number of tasks completed successfully per participant–line chart pair was 2.05 ± 1.90 for tap-to-hear and 8.15 ± 1.09 for melodic line tracing. When aggregating results per participant, the mean was 4.10 ± 3.54 for tap-to-hear and 16.3 ± 2.11 for melodic line tracing. A two-tailed Wilcoxon signed-rank test [320] confirmed significant differences in both cases: for participant–line chart pairs, the Wilcoxon statistic was 0.0 with a p-value < 0.001, and for per-participant aggregation, it was 0.0 with a p-value of 0.002 ($\alpha < 0.05$). The null hypothesis was rejected in both analyses, indicating that the melodic line tracing interface was significantly more effective than tap-to-hear. The per-participant analysis was conducted to account for individual variability across line charts, making it more challenging to detect significant differences, thus further reinforcing the superior effectiveness of the melodic line tracing UI.

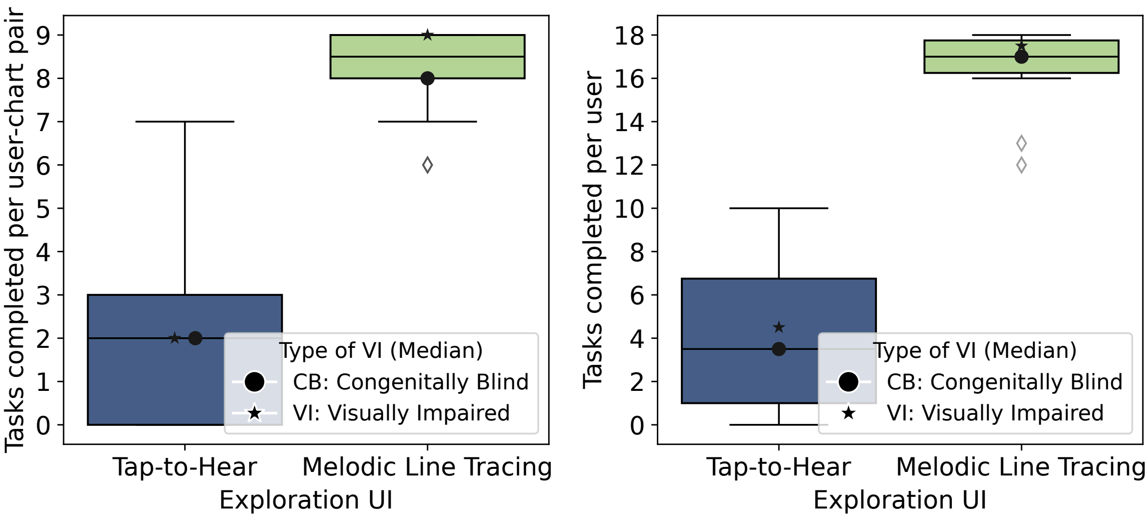

Figure 5.14.: UI Effectiveness Analysis. Left: number of tasks completed successfully per user-line chart pair for each UI. Right: number of tasks completed successfully per user across all charts for each UI.

To gain a deeper understanding of user performance, effectiveness was analysed across the three task types (1, 2, and 3) (Figure 5.15, left plot). The mean number of total tasks completed correctly per participant was 7.0 ± 0.94 for Type 1, 6.9 ± 0.74 for Type 2, and 6.5 ± 3.60 for Type 3. A Friedman test was conducted to assess the significance of these differences, accounting for the small sample size and non-normal distribution of the data. The results yielded a test statistic of 0.19 and a p-value of 0.91, indicating no significant differences between the task types.

Expanding upon this analysis, performance was assessed across the different task types but grouped by UI (Figure 5.15, right plot). For the Tap-to-Hear UI, the mean number of tasks correctly completed per user was 1.0 ± 0.94 for Type 1, 0.9 ± 0.74 for Type 2, and 2.2 ± 2.20 for Type 3, with a Friedman test yielding a test statistic of 3.27 and a p-value of 0.20, indicating no significant differences within this interface. In contrast, for the Melodic Line Tracing UI, the mean number of tasks completed correctly per user was 6.0 ± 0.00 for Type 1, 6.0 ± 0.00 for Type 2, and 4.3 ± 2.11 for Type 3, with a Friedman test yielding a test statistic of 14.00 and a p-value of < 0.001, revealing a significant difference for Type 3 compared to the other two tasks types. This analysis demonstrates that while the Melodic Line Tracing UI outperforms the Tap-to-Hear UI, it still highlights the significant challenge users face in complex tasks, such as determining the number of distinct intersections with other lines (Task Type 3).

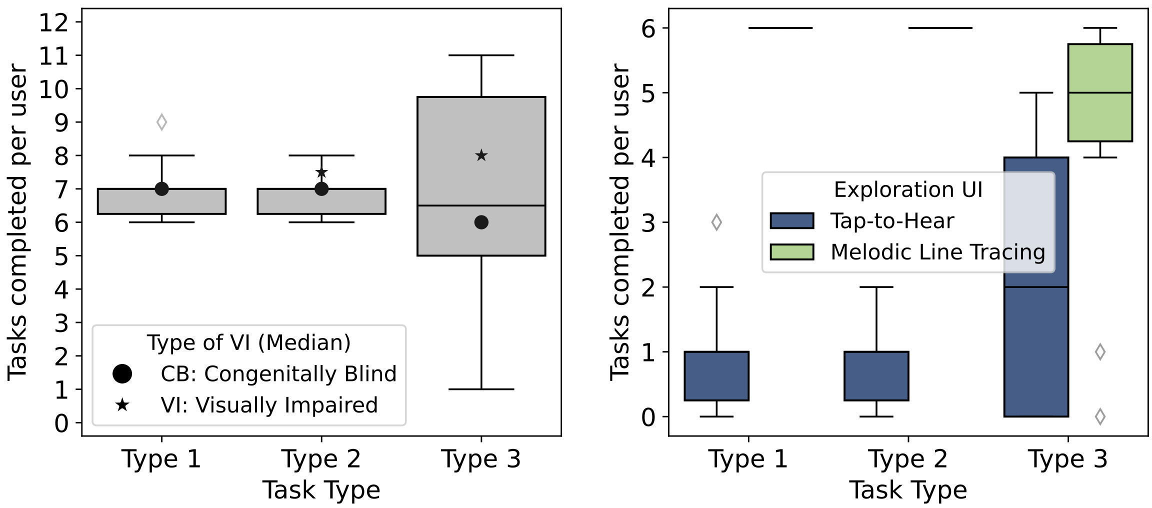

Figure 5.15.: Task Type Effectiveness Analysis. Left: Distribution of tasks completed successfully per participant for each task type. Right: Distribution of tasks completed successfully per participant for each task type and grouped by exploration UI.

Overall, the analysis indicates that the melodic line tracing UI significantly outperforms the tap-to-hear UI in terms of task completion effectiveness across all evaluated perspectives.

UI Efficiency Analysis

UI efficiency was assessed by examining both cognitive load and time efficiency. Time efficiency was measured by recording the time duration users took to complete all nine tasks on each line chart (9-Tasks Duration). Cognitive load was evaluated using normalized NASA-TLX scores (Figure 5.16).

The mean 9-tasks duration per user-line chart pair was 819.45 ± 290.29 seconds for the Tap-to-Hear interface and 719.85 ± 255.67 seconds for the Melodic Line Tracing interface (Figure 5.16 - left plot). The maximum duration a participant took to complete all tasks was 1360 seconds (22.67 minutes), and the minimum duration was 294 seconds (4.9 minutes), both using the Tap-to-Hear interface. A two-tailed Wilcoxon signed-rank test was conducted to assess whether there was a significant difference in time efficiency between the two user interfaces [320], chosen for its suitability with non-normally distributed data. The results yielded a Wilcoxon statistic of 66.0 and a p-value of 0.154, indicating no significant difference in the mean duration (9 tasks) per user-line chart pair between the two user interfaces ($p > 0.05$).

Building upon the established methodology, NASA-TLX questionnaires were employed to evaluate subjective workload, with scores normalized to a 0–100 scale using a distributed weighted approach consistent with standard practices, where lower scores indicate reduced cognitive load. Participants reported a mean NASA-TLX score of 46.58 ± 22.00 for the Tap-to-Hear UI and 25.50 ± 21.88 for the Melodic Line Tracing UI (Figure 5.16 - right plot). This disparity highlights the notably lower cognitive load associated with the Melodic Line Tracing interface. A two-tailed Wilcoxon signed-rank test [320] confirmed this finding (Wilcoxon statistic = 0.0, $p = 0.002$), indicating statistically significant differences in cognitive load between the two user interfaces ($p < 0.05$).

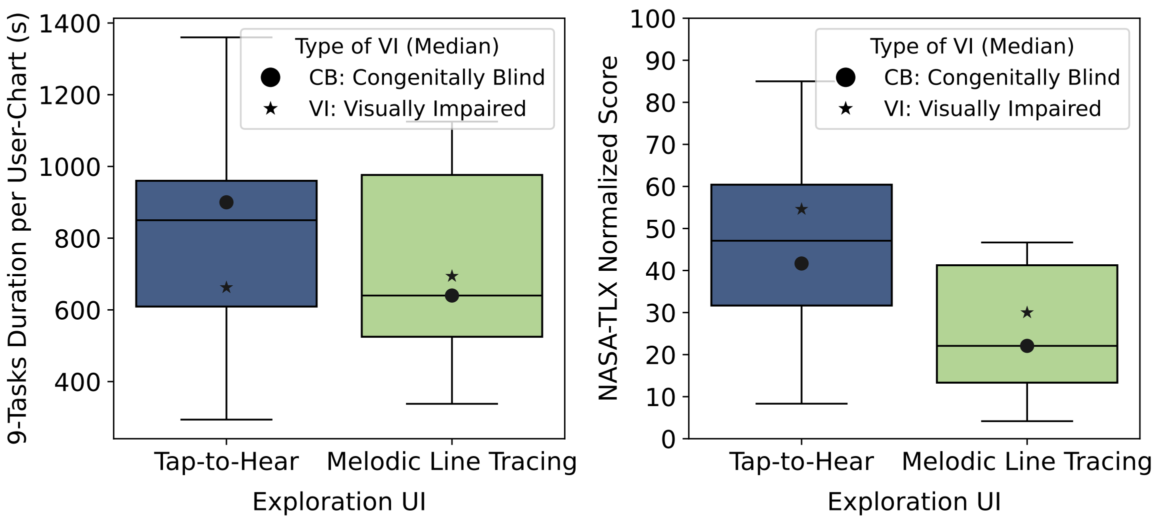

Figure 5.16.: UI Efficiency Analysis. Left: Duration of all nine tasks per user-line chart pair for each exploration UI. Right: Distribution of normalized NASA-TLX scores per participant for each exploration UI.

UI Satisfaction Analysis

UI satisfaction was assessed by examining SUS scores, semi-structured interview utility ratings, and qualitative feedback from the interviews (Figure 5.17).

Normalized (0-100 scale) SUS (System Usability Scale) scores were employed to evaluate user satisfaction, where higher scores indicate better usability. Participants reported a mean SUS score of 69.50 ± 19.68 for the Tap-to-Hear UI and 86.75 ± 10.07 for the Melodic Line Tracing UI, with the latter reflecting a level of usability considered good according to previous research [23] (Figure 5.17 - left plot). A two-tailed Wilcoxon signed-rank test yielded a Wilcoxon statistic of 0.0 and a p-value of 0.002, indicating a significant difference in SUS scores between the two user interfaces ($p < 0.05$), highlighting the superior satisfaction associated with the Melodic Line Tracing UI.

During semi-structured interviews, participants were asked to rate the usefulness of each UI for learning and exploring line charts on a scale from 1 to 5 (1 = not effective, 5 = very effective). Participants reported a mean utility rate of 3.0 ± 0.94 for the Tap-to-Hear UI and 4.5 ± 0.97 for the melodic line tracing UI (Figure 5.17 - right plot). A two-tailed Wilcoxon signed-rank test yielded a Wilcoxon statistic of 0.0 and a p-value of 0.010, indicating a significant difference in utility scores between the two interfaces ($p < 0.05$), highlighting the utility superiority associated with the proposed Melodic UI. Notably, one outlier participant rated both UIs with a utility score of 2: "I do not like to always have one finger straight. These conditions can still be improved." – (P6, CB), underscoring the potential for targeted enhancements in both UIs.

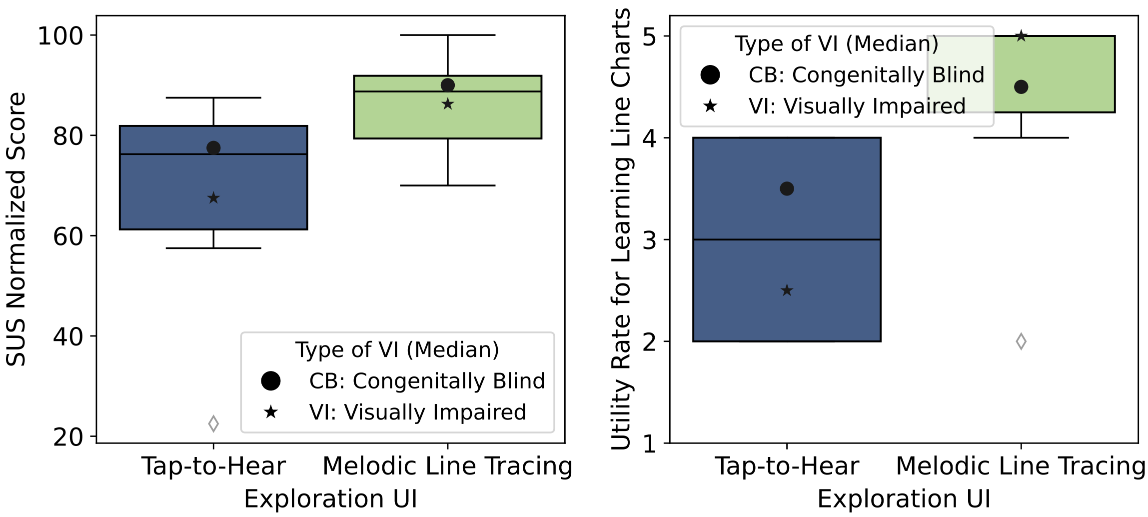

Figure 5.17.: UI Satisfaction Analysis. Left: Distribution of normalized SUS scores per participant for each exploration UI. Right: Distribution of utility ratings for learning line charts per participant for each exploration UI.

Participants' comments further reinforce the significantly higher perceived satisfaction and usefulness of the Melodic Line Tracing UI compared to the Tap-to-Hear UI. The latter was associated with frustration and limitations, as noted by users: "It would be nice to explore with more than one finger; to tell the maximums apart, I use two hands, and I have to move my finger away from the graphic constantly." – (P3, VI), "With this user interface following the line is difficult enough and if you have to do more things it is an overflow for my brain. For easy charts, it is okay, but if you want more, the UI is not enough." – (P2, CB), "I even forgot about these (min/max) because I am too focused on getting the line traced by exhaustively asking the current line name. I cannot do these two tasks at the same time." – (P4, VI), and "I was not able to get the length of the line most of the time with the tap-to-hear UI." – (P5, VI). In contrast, participants highlighted the Melodic Line Tracing UI as intuitive and practical, stating: "Very helpful, you're using multiple channels, sound and speech. It is very intuitive." – (P2, CB), "I found it very good because it is able to help me access information that was not possible before." – (P6, CB), and "Interesting what is possible now! Cool! As someone who is not into systems and technology, this user interface can still be helpful and very descriptive to understand these graphics." – (P10, CB).

Melodic UI Feature Usefulness Analysis

To further assess the perceived usefulness of the Melodic Line Tracing UI, participants individually rated the utility of its three core functionalities on a scale from 1 (not helpful) to 5 (very useful). The synth melody environment received a mean rating of 4.80 ± 0.42, pitch trace guidance was rated 4.7 ± 0.95, and line boundary feedback received 4.9 ± 0.32. Overall, participants provided consistently high ratings across all features, suggesting strong acceptance and perceived utility. A Friedman test ($\chi^2 = 0.80$, $p = 0.67$) showed no significant differences among the three functionalities. This suggests that all features were equally well received and that no single functionality stood out as more or less valuable than the others. Notably, one participant rated pitch trace guidance with only a 2, preferring the synth melody environment alone for line tracing due to having perfect pitch: "The musical note already helped me to get the information I wanted." – (P6, CB). Such variations highlight the importance of accounting for individual user preferences and capabilities in UI design.

Line Charts Analysis

The individual line charts were analysed based on task completion rates and the time to complete nine tasks (Figure 5.18). Friedman tests for effectiveness (tasks completed) and time efficiency (9-task duration) revealed no significant differences between the charts: effectiveness: $\chi^2 = 1.37$, $p = 0.71$; time efficiency: $\chi^2 = 6.46$, $p = 0.09$. Participants rated the difficulty of the evaluation charts from 1 (easy) to 5 (challenging), with a mean of 3.8 ± 0.79, suggesting that, while the charts were moderately demanding, users still believed more complex charts could be explored with the UIs: "There must be more difficult graphics out there." – (P8, CB), "Graphics can still have more intersections." – (P9, VI).

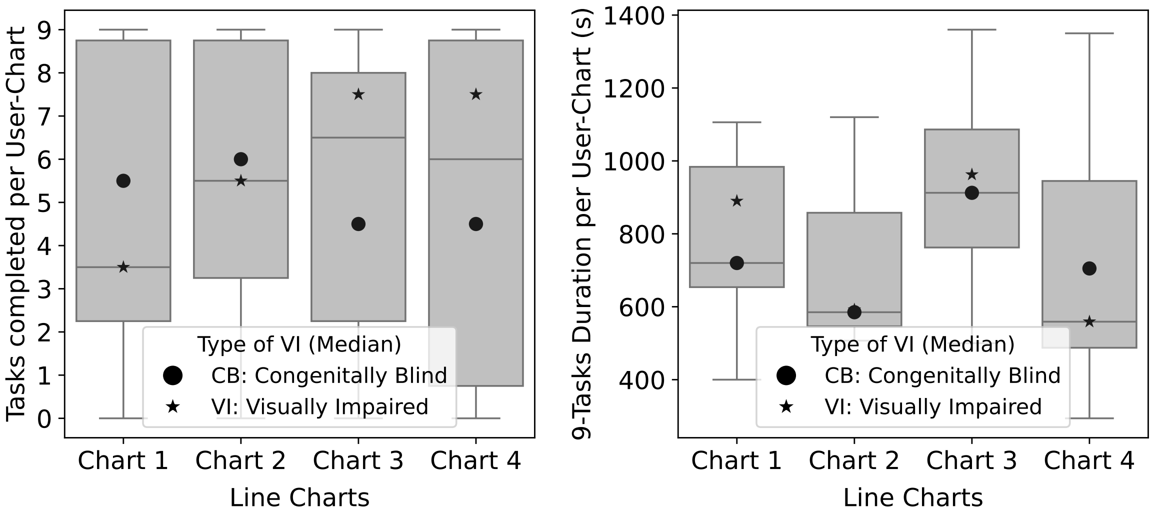

Figure 5.18.: Line Charts Analysis. Left: Tasks completed successfully per participant-line chart pair for each evaluation line chart. Right: Duration of all tasks per user-line chart pair for each evaluation chart.

Expanding Applications of Line Tracing Interfaces

All users indicated a preference for using the Melodic Line Tracing UI for exploring line charts, despite some having prior experience with other methods (3 participants). When discussing its scalability, participants suggested a variety of potential applications across different contexts beyond presenting mathematical data: "Definitely, I can see it in very use-cases. Mathematical graphs, maps, and metadata such as the number of inhabitants distribution per city." – (P6, CB). The most frequently mentioned contexts were orientation and mobility, including floor plans and country maps: "Regions instead, different tones for each region. In floor plans, each room has a distinct sound." – (P1, CB), "One great context is to use it with maps, where line borders can interact with line tracing." – (P9, VI). Educational contexts also emerged as a strong theme: "Could be used for learning control with little games for children, where you associate sounds as rain to specific elements." – (P2, CB), "I see the potential to be used for educational purposes with young children that are starting to work with graphics since it has the "playable" aspect" – (P7, CB).

5.3.3. Discussion

Superior Performance of Melodic Interface - The Melodic Line Tracing Exploration represents a significant advancement in supporting individuals with BVI in interpreting and exploring complex line charts. Results indicated a significant improvement in effectiveness and user satisfaction compared to the tap-to-hear solution. On average, users completed four times more tasks correctly with the melodic exploration UI than with the tap-to-hear interface, highlighting the magnitude of this improvement. The interface enabled users to effectively identify critical elements such as maximum and minimum values, accurately detect intersections, and trace lines with a high degree of precision. By centring the interactions around complex charts, the Melodic Line Tracing Exploration further emphasized its impact, empowering users in ways previously considered unattainable: "Interesting what is possible now!" – (P10, CB). Notably, this increased effectiveness and user satisfaction did not come at the cost of prolonged interaction times. On the contrary, the interface demonstrated improved time efficiency (but not significantly). This finding challenges the assumption that more feature-rich user interfaces inevitably lead to longer interaction durations. With appropriate training, such user interfaces have the potential to exceed the performance of standard assistive UIs, thus contributing to the advancement of emerging technologies in the BVI field.

Impact on Graphics Complexity Perception - The impact of the proposed interface was profound, as it significantly altered users' perceptions of graphic complexity. In contrast to findings from a previous study [239], where participants found charts with as few as 6 to 9 lines to be overwhelmingly complex due to the limitations of prior UIs, the melodic line tracing interface empowered users to engage with even more challenging charts. These charts featured a higher number of intersections and lines with more zigzagging and fluctuations than those used in the earlier study. Yet, users could navigate them with greater efficiency and reported high confidence: "There must be more difficult graphics out there." – (P8, CB), "Graphics can still have more intersections." – (P9, VI). This shift underscores the critical role that tailored and human-centred design-based user interfaces play in improving accessibility and usability, challenging the prevailing limitations in current accessible design for complex visual data.

Empowering All Users - The user interface was designed to empower both advanced and novice users, ensuring it did not 'cut the wings' of more experienced individuals while remaining intuitive for beginners, as demonstrated by the results and use of a diverse participant sample. This highlights the critical importance of considering users' preferences and experiences in developing a universal UI that serves a broad spectrum of users rather than being tailored to a specific subgroup. Despite successfully addressing the challenge of interpreting complex line charts, users still identified areas for improvement. It is reasonable to conclude that the Melodic user interface could be further refined through iterative development, continuing to follow a human-centred design approach to ensure it meets the evolving needs of its diverse user base.

5.4. CONCLUSION AND FINDINGS

Understanding and exploring complex line charts presents considerable challenges for individuals with BVI. While Tactile Graphic Readers offer potential solutions, no standard user interface currently exists that effectively, efficiently, and satisfactorily supports the interpretation of realistic, complex line charts. To advance this technology and address the research gap, a tailored, scalable, human-centred interface is needed.

To address this challenge, a human-centred trigger-trace line exploration UI was developed and evaluated against the standard tap-to-hear graphic exploration UI in a preliminary study with four BVI participants. Despite offering additional details on shapes and intersections, which participants found helpful, the trigger-trace UI did not improve effectiveness compared to the standard UI. Instead, it led to a higher perceived workload and longer task durations. Both UIs performed well with straightforward (up to 3 lines) line charts but struggled with more complex ones. Key limitations included the inability to determine the start and end boundaries of each line and the lack of an intuitive method for recognising intersections. Findings highlight the pressing need for a solution that enables BVI individuals to explore and interpret real-world, complex line charts effectively.

Building on these findings, key issues were addressed, and user feedback was incorporated into the development of the human-centred melodic line tracing exploration UI, which introduced three new features: a synth melody environment, pitch trace guidance, and line boundary feedback. This melodic exploration UI was then evaluated against the tap-to-hear UI in a study with 10 BVI participants, focusing exclusively on understanding real-world line charts with high intersections and fluctuations. Statistical analysis revealed that the melodic exploration UI was significantly more effective and satisfactory in learning complex charts than the tap-to-hear approach without prolonging interaction times. Both beginners and advanced users successfully learned and understood the complex charts, highlighting the UI's universal design and its ability to accommodate diverse user preferences. By the end, users perceived the line charts as less complex, demonstrating the interface's impact in significantly altering their perception of graphic complexity.

These findings provide meaningful insights into the design of audio-tactile exploration systems aimed at addressing complex, real-world challenges rather than simple, theoretical ones. To deepen our understanding, we now turn to Research Question 2 and explore its sub-questions, each addressing a critical aspect of accessible line-chart learning and exploration for BVI users.

Answering Research Question 2

RQ2.1: To what extent can current state-of-the-art audio-tactile UIs assist BVI individuals in efficiently and effectively learning and exploring line charts?

The current state-of-the-art audio-tactile UI, tap-to-hear exploration, proved adequate for simple line charts (with up to five lines and minimal intersections or overlaps) but was ineffective for more complex ones (see Section 5.2). Both usability studies substantiated the tap-to-hear exploration limitations in facilitating the learning and exploration of complex line charts (see Section 5.3). This was particularly evident in the second study, where users explored only complex charts, achieving a mean task completion rate of just 2 out of 9 with this UI.

RQ2.2: What key design factors contribute to an effective dynamic audio-tactile user interface for assisting BVI individuals in learning complex line charts while optimising both efficiency and user satisfaction?

Results from both usability studies indicate that line-tracing guidance is a key design factor to assist BVI users to effectively explore complex line charts (see Sections 5.2 and 5.3). Additional features, such as global max/min markers and boundary feedback, further enhance usability without increasing workload.

However, line tracing alone is insufficient, as users also need a clear representation of multiple lines and intuitive intersection recognition. The Trigger-Tracing UI attempted to address this but introduced redundancy in intersection feedback, leading to confusion, increased workload, and reduced efficiency and satisfaction. In contrast, the Melodic Tracing UI assigns each line to a distinct instrument tone, effectively handling overlaps without ambiguity. A key design factor was ensuring the melodies were both distinguishable and harmonically pleasant, reducing workload and improving effectiveness. Statistical analysis revealed that Melodic UI was significantly more effective and satisfactory in learning complex charts than the tap-to-hear approach without compromising efficiency.

6. CRAFTING 2D DYNAMIC TRAVEL ROUTE LEARNING

Effective pre-travel route planning is crucial for independent mobility, particularly when navigating unfamiliar locations. Learning travel routes in 2D maps is essential for this process, yet it remains particularly challenging for individuals with BVI, especially when dealing with large maps and complex routes. Building on prior work, a tap-to-hear-based map exploration UI for 2D refreshable tactile pin displays was implemented and evaluated in the context of learning routes on network maps. An initial user study with 9 BVI participants revealed that, while promising, the tap-to-hear UI did not fully address the challenge, with users expressing frustration and a need for more comprehensive data representations and faster solutions. To tackle these challenges, a new dynamic UI—immersive map-route exploration—was developed and evaluated against the tap-to-hear UI in a second user study with 12 BVI participants, focusing on learning complex routes in large network maps. The immersive UI outperformed the tap-to-hear UI in efficiency, effectiveness, and satisfaction, allowing users to learn and explore real-world routes after just 15 minutes of training. Nevertheless, participants showed varying opinions on which features were most impactful and in UI's scalability, highlighting the challenges in designing universally ideal user interfaces.

This chapter includes content from a publication in PETRA 2023 [238].

6.1. PRE-TRAVEL: LEARNING TRAVEL ROUTES IN 2D MAPS

Orientation and mobility have been among the most prominent topics in assistive technology and the BVI community, as travelling in unfamiliar locations remains a significant challenge and one of the most common life-quality impacts for the blind [161, 100]. Pre-travel learning, a vital aspect of this research field, encompasses all preparatory activities before the journey, including learning route layouts, key landmarks, and transfer points to enhance confidence and efficiency in real-world navigation. Therefore, practical solutions that support pre-travel learning are essential for all travellers seeking to navigate unfamiliar environments autonomously [148, 282, 54, 58, 260].

This research focuses on route learning in the context of pre-planning rather than on-site navigation. Even within pre-planning, the focus is not on orientation and mobility, spatial cognitive maps, or turn-by-turn navigation but on learning and interpreting 2D graphical representations of travel routes. This focus aligns with the broader objective of enhancing graphics accessibility, which is central to this dissertation. The computation of the most accessible and faster routes is beyond the scope of this work.

6.1.1. Method-Interface Spectrum

Past research on tactile graphic readers and 2D refreshable tactile pin displays has explored diverse solutions to assist BVI users in learning and interpreting travel routes. Such research has addressed various contexts, including indoor floorplans, city maps, general cartographic representations(OpenStreetMap or Google Maps), and metro network maps.

UI Research in Exploring Maps and Learning Routes

Although audio-textual route descriptions are helpful [304], learning routes and exocentric geographic spaces from tactile graphics is a common and more effective approach in mobility training for BVI persons [138, 67]. However, even with large tactile surfaces, tactile-only interfaces are limited in information representation, prompting the development of more efficient solutions, such as multimodal (audio-tactile) map-route user interfaces [138, 58, 59, 124]. The established standard involves using tactile information to represent landmarks and the route itself, enhanced with additional pinpoint audio details. Known as **tap-to-hear exploration**, this solution allows users to explore map routes and access pinpoint details through touch-based interactions [312, 5, 57, 58, 59, 215, 264, 148, 328, 124, 260], infrared frame detection [89, 90], or camera-based fingertip detection [274, 238], depending on the device's capabilities.

Beyond static audio-tactile map-route representations, 2D refreshable tactile pin displays, along with other devices, have played a crucial role in the emergence of dynamic approaches. These include the introduction of zooming and panning controls [90, 89, 332], leveraging the dynamic tactile surfaces of such devices, and elevating the interaction for map-route exploration. Panning on fast 2D refreshable tactile displays allows users to explore new areas without losing focus, as the map updates based on finger movement while maintaining contact with the focus area [328, 262, 331]. Related research has implemented such operations through tactile buttons, drag-pinch gestures, and continuous tangible sliders, enabling dynamic map updates via refreshable tactile displays or through technologies like landmark robots that reposition on tangible tabletop interfaces [90, 89]. Another dynamic approach that emerged was the implementation of layout rendering manipulation, designed to offer users different levels of detail and information, from broad overviews for an initial perspective to filtering specific map elements for in-depth exploration [264, 260].

Tap-to-hear exploration, combined with zooming, panning, and rendering manipulation, collectively defines the state-of-the-art approach for accessing graphic information in 2D refreshable tactile pin displays and similar technologies, known as the **Generic Tap-to-Hear Graphic Exploration UI**. However, beyond generic graphic accessibility UIs, and driven by the growing interest among BVI individuals in effectively learning routes on 2D maps [137], prior research has led to the development of specialized solutions aimed at enhancing map-route interpretation and learning. These include the enlargement of the route's width, highlighting and improving its tactile prominence from the other map elements [148]. Blinking pins through a single-pin cursor that moves dynamically along the route path at regular intervals have been utilized, proving highly effective in highlighting the direction of travel and facilitating map-route learning [137, 148]. Nevertheless, such dynamic interfaces require a fast pin refresh rate and are not scalable to all 2D refreshable tactile pin displays.

Research Gap: Network Maps

To clarify the research gap, it is essential to examine the graphical contexts prioritized in prior research on route-learning user interface development. Most contributions have focused on indoor floor plans, general cartographic representations, and city maps, while network maps have received comparatively less attention.

Indoor accessibility information remains critically needed by the BVI community due to the lack of available indoor maps [282, 95, 209, 283]. As a result, prior research also focused on developing user interfaces in the context of learning indoor floor plans [54, 260].

Significant UI development has also been conducted in the context of SVG-based city maps, which, beyond streets and buildings, comprised distinct points of interest, such as museums, public transport, and rivers [137, 59, 58].

Efforts to extend the benefits of online geo-data services like OpenStreetMap (OSM) [131], Google Maps and MapQuest to the BVI community have garnered significant attention, spurring extensive research into user interfaces tailored to general cartographic representations [331, 312, 332, 264, 328, 148].

Network maps have received fewer contributions compared to the aforementioned contexts. Moreover, studies addressing this area often employed simplified, fictive network maps with limited stops and connections [90], which, while contributing to the challenge, fail to address the complex, real-world problems faced by BVI individuals. Due to this limited coverage in prior research, this work explicitly examines network maps as a medium for learning travel routes. Floor plans, city maps, and general cartographic representations were not the focus of this dissertation. Network maps were also chosen due to their structured, interconnected pathways that require distinct exploration strategies, making them an ideal case study for evaluating advanced dynamic audio-tactile user interfaces.

6.1.2. UI Design: Map-Route Exploration

Unlike the other user interfaces in this dissertation, this section presents the design and implementation of interfaces on 2D refreshable tactile pin displays rather than on 2D tactile graphic readers. This shift aimed to explore a broader range of contexts for applying 2D dynamic audio-tactile UIs. Additionally, the Tactonom Pro device, which has not yet been investigated in research contexts, was examined, providing an opportunity to leverage its unique features and potential for dynamic tactile interfaces. Ultimately, this section details the design of two distinct user interfaces aimed at assisting BVI individuals in exploring routes on 2D maps: the **Tap-to-Hear** Map-Route Exploration UI (Figure 6.1) and the **Immersive** Map-Route Exploration UI (Figure 6.2).

Tap-to-Hear Map-Route Exploration UI

Building on previous work in 2D map exploration and travel-route learning with 2D refreshable tactile pin displays, the Tap-to-Hear Map-Route Exploration UI was designed and implemented (Figure 6.1). This user interface was originally developed within the context of cartographic representations, specifically OpenStreetMap data [238]. However, given that this area has already been addressed in related work [331, 312, 332, 264, 328, 148], the focus was shifted to transportation network maps, a topic less explored in the existing literature on 2D refreshable tactile pin displays. The explored network maps are SVG-based, making this shift not only a contribution to filling a research gap but also a natural alignment with the dissertation's focus on graphics accessibility.

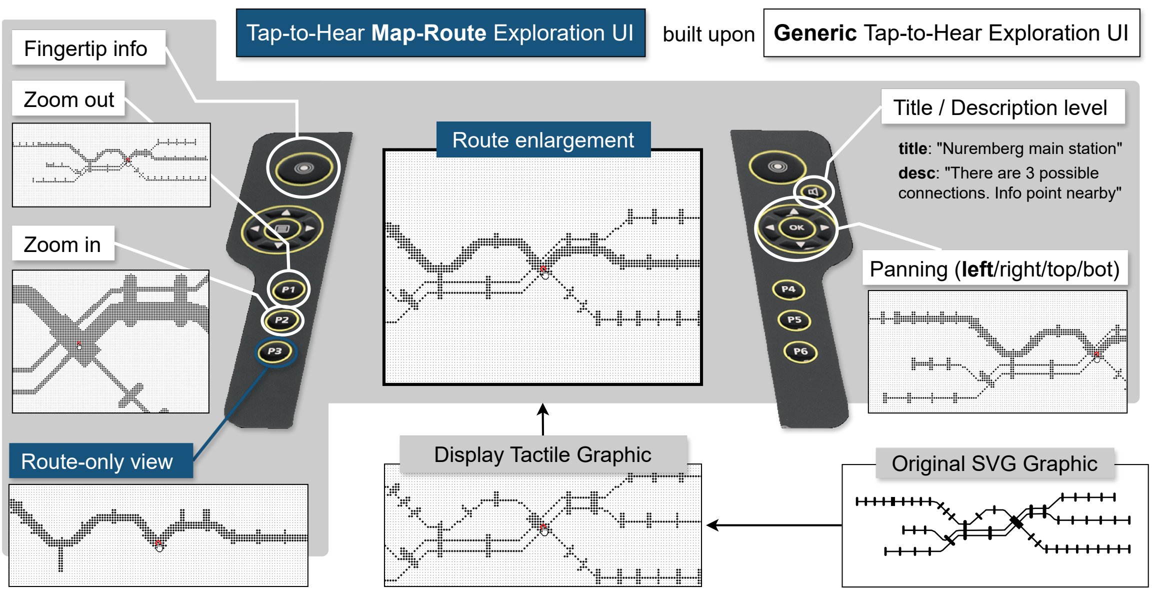

Figure 6.1.: Tap-to-Hear Map-Route Exploration UI. Built upon the generic Tap-to-Hear Graphic Exploration UI, this interface introduces two key features used in prior research: route-width enlargement [148] and the ability to isolate the travel route by removing background lines for focused exploration [264].

Although contextualised to learning routes in network maps, the tap-to-hear map-route UI incorporates baseline components from the generic tap-to-hear graphic exploration UI, which was already applied to 2D tactile graphic readers (Tactonom Reader) and investigated in chapters 4 and 5.

This includes fingertip-based information access, allowing users to pinpoint desired elements on the map and hear their corresponding names, as well as information level filtering, where users can choose to hear either a simple title or a more detailed description. In the context of network maps, for example, this means users can hear the name of the stop they are pointing to or get additional details, such as the name of possible transfer connections or nearby points of interest (POIs). Other components that are not feasible for 2D tactile graphic readers but are implemented in the generic tap-to-hear graphic exploration UI for 2D refreshable tactile pin displays include dynamic page navigation. This allows for zooming in, zooming out, and panning (left, right, up, down) through the SVG content, made possible by the refreshable tactile display. For the Tactonom Pro implementation, SVG content is rendered through the open-source Apache Batik toolkit.

Beyond the baseline features of the generic tap-to-hear exploration UI, the tap-to-hear map-route exploration UI introduces two key features for learning travel routes in 2D maps. One feature is the enlargement of the route width, enabling users to distinguish the main route from other network lines, as investigated in related work [148]. In this implementation, the route width is designed to be equivalent to two pins on the tactile surface when the graphic is zoomed out, with all other lines set to a width of 1. The SVG width parameter for the main route is three times that of the other lines, which is used and noticeable when the page is zoomed in. The second feature is the option to render only the route for simplicity, removing all other elements from the tactile surface, as explored in related work [264]. This is achieved by not representing all SVG elements that are not the route path element through the Apache Batik toolkit.

Further solutions from related work (e.g., blinking pins along travel route [137, 148]) were not implemented, as these rely on fast 2D refreshable tactile pin displays and are unsuitable for slower devices like the Tactonom Pro. Instead, the design prioritises broader applicability across diverse assistive technologies.

Immersive Map-Route Exploration UI

Through close collaboration with BVI individuals within the work environment and drawing on the outcomes of the investigation raised in section 6.2, the Immersive Map-Route Exploration UI was designed and implemented (Figure 6.2). The aim was to assemble a UI that could effectively and efficiently assist BVI users in learning both simple and complex travel routes, surpassing the limitations of the state-of-the-art-based tap-to-hear UI and contributing to bridging the existing research gap.

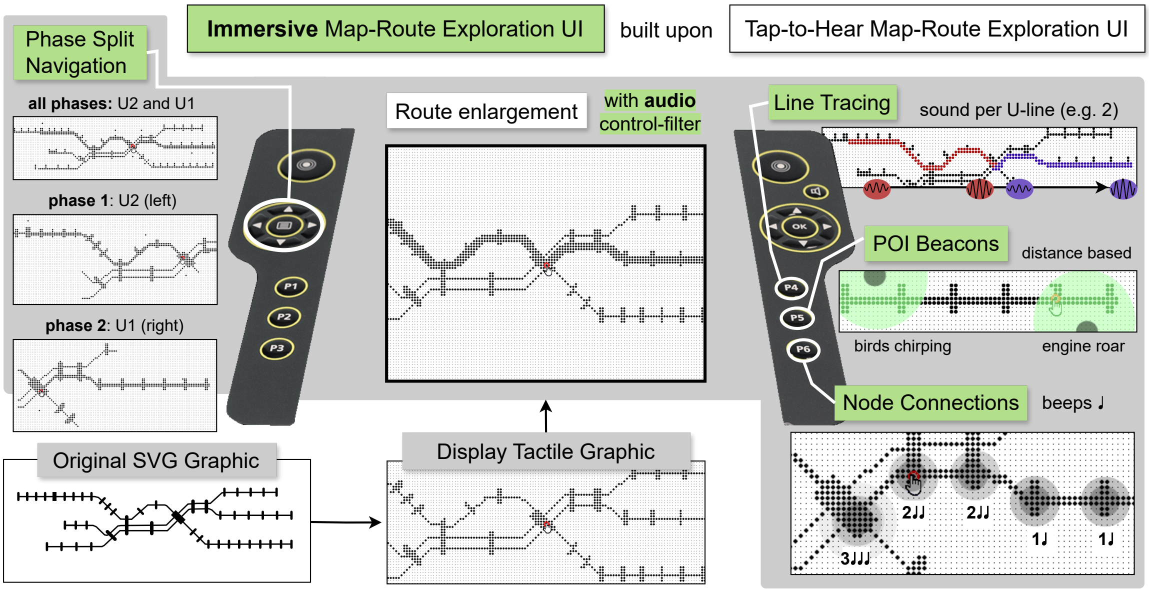

Figure 6.2.: The Immersive Map-Route Exploration UI extends the tap-to-hear UI with five features: phase-split navigation for immersive route visualization, and four audio enhancements—line tracing, POI (Point of Interest) beacons, node connection feedback, and the ability to filter or mute these elements. Other UI features are excluded for clarity and shown in Figure 6.1.

The immersive map-route exploration UI builds upon the previously developed tap-to-hear map-route exploration UI, retaining all its features and introducing new dynamic components aimed at optimizing the use of audio-tactile information and addressing information overload. New features include phase-split navigation and four audio enhancements: line tracing, POI beacons, node connections, and element filtering/muting.

The **phase-split navigation** feature divides the route into phases, each representing the underground lines it passes through. Users can explore each phase individually, with centred zoom-in views, allowing for a more detailed exploration. This approach eliminates the need for manual zoom adjustments, providing more targeted route information. When switching phases, the Sonoice audio pinpoint navigation UI (see Figure 4.6) directs the user's fingertip to the starting point of the new phase, improving efficiency. Since the Tactonom Pro enables hands-on interaction during the refresh, users can begin navigating with audio cues while the display updates, effectively countering the limitations of slow refresh rates.

The audio enhancements enable dynamic interactions during route exploration, moving beyond the limitations of slow, repetitive tap-to-hear actions. The **line tracing** feature utilizes pitch-trace guidance (see Section 5.1.2), where a continuous baseline beep (instrument-based) serves as the reference sound, with frequency increasing as the user's fingertip moves from the starting point toward the next stop where an underground line change occurs. Upon reaching this transfer stop, the baseline beep changes to a different but distinct tone, signalling the transition to a new underground line. When exploring a single phase, the pitch variation occurs between stops along the same line, providing the user with detailed auditory feedback to track their movement within the line, ensuring that no segment is overlooked.

Audio **POI** (Point of Interest) **beacons** are used to enhance the immersive experience and provide contextual information. As the user moves along the route, the UI dynamically plays background sounds corresponding to nearby points of interest. For example, the sound of flowing water might indicate the proximity of a river, birds chirping could signal a nearby park, or the distinct sounds of a stadium indicate the presence of a sports venue. The aim is to use audio cues that mirror natural environmental sounds, providing immediate feedback to enhance situational awareness and immersion without overwhelming the user.

The **node connections** feature provides dynamic audio feedback at each stop. A distinct beep signals the user's arrival at a stop, with the number of beeps corresponding to the number of possible connections at that stop. For stops with three connections, three fast consecutive beeps are played, while stops with fewer connections trigger a single short beep. The aim of this approach is to shift information that would traditionally be conveyed through tactile graphics to the auditory domain, allowing the user to understand the stop's connectivity without relying on tactile maps. In the overview (all phases) view, audio feedback is triggered only at the route transfer stops, as well as the starting and ending stops—ensuring users immediately understand where the most relevant locations are along the route.

To increase flexibility and user control, the immersive UI has the option to **filter and mute** the previously described dynamic audio features: line tracing, POI beacons, and node connections. The aim is to provide users with the ability to adjust the auditory experience based on their individual needs. For less experienced users, this feature allows them to start with fewer sounds, reducing potential overwhelm and enabling a gradual acclimation to the system. For instance, users could prioritize line tracing while temporarily muting POI beacons or node connection sounds. For experienced users, or as users become more familiar, they may choose to activate all available sounds simultaneously.

The immersive UI enables these new features by utilizing a custom JSON-based architecture to represent the travel route and its associated information (Figure 6.3). While the tap-to-hear interface relies solely on the map SVG file and its "path" element to represent the travel route, the immersive UI uses the SVG file along with an additional JSON format to define the route instead, allowing for the integration of richer, feature-specific information.

The JSON architecture used by the immersive UI consists of two main elements: "nodes" and "beacons". Nodes represent specific points along the route and are integral to defining the path in the SVG file, with each node containing x and y coordinates that correspond to the spatial layout of the route in the original SVG. Each node can be classified as either an *AUDIO-NODE* or a *SILENT-NODE*. *AUDIO-NODE* nodes, in addition to being part of the route structure, are associated with predefined OPUS audio files that play when the user interacts with them. These include an "audio-ambient" sound that triggers when the user pinpoints the node (Node Connections beep), an "audio-beep-line" which triggers in a loop when the user pinpoints the line (Line Tracing beep), and an "audio-line" which plays when the user selects the line (such as the name of the underground line, e.g., "U2"). The "audio-beep-line" attribute is also used to classify the nodes into the route phases for the Phase Split Navigation feature. *SILENT-NODE* nodes, on the other hand, do not trigger any sounds and solely form the shape of the route. The order of nodes in the JSON file defines the direction of the route. The nodes also include a "region" attribute (e.g., University, River, or City Center), which is used to determine the appropriate context for playing beacon sounds. Beacon elements, like nodes, have a position (x-y coordinates), an "audio-ambient" sound, and a region attribute. However, they are not used to define the route or serve as connection points along it. Instead, beacons are external markers that trigger specific sounds when the user's position aligns with their proximity. The associated "audio-ambient" sound plays in a loop as the user's route position enters the same region as the beacon's region, with the sound getting louder as the user's route position gets closer to the beacon.

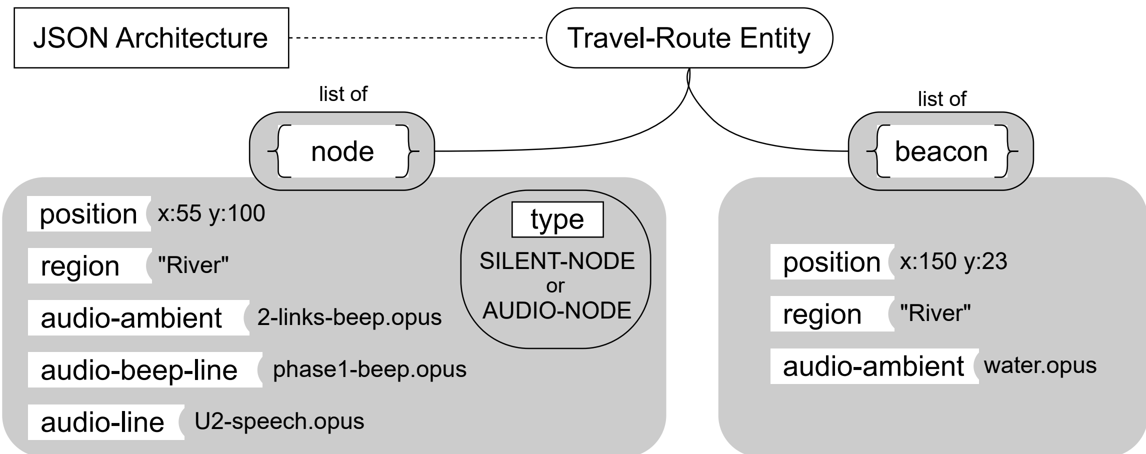

Figure 6.3.: JSON architecture for representing travel-route data in the immersive UI. Including attribute value examples for the beacon and node elements to enhance understanding of their format and functionality.

6.2. LEARNING THROUGH TAP-TO-HEAR MAP-ROUTE EXPLORATION

Employing a human-centred design methodology, an initial user study was conducted to assess and validate the performance of the standard Tap-to-Hear map-route exploration UI (Figure 6.1). This study focused on evaluating the significance of the UI in aiding individuals with BVI in learning and navigating realistic travel routes on metro network maps. The objective was to determine whether existing state-of-the-art user interfaces are capable of handling real-world data and addressing practical challenges while gathering valuable user feedback to drive the creation of an improved user interface aimed at addressing the research gap.

Participants

The study included 9 BVI participants (three females, six males; Table 6.1) recruited through local educational centres for the blind in Nürnberg (BBS). Interested individuals received study details and participated if they reported a medical diagnosis of visual impairment or blindness, as visual acuity was not directly measured. Exclusion criteria included being under 18, substance abuse and medical conditions affecting cognition, hearing, communication, touch, or motor skills. The KIT University ethics committee approved the study, and all participants provided informed consent. Self-reports categorised participants into two groups: four congenitally blind (CB) and five visually impaired (VI). Additionally, participants' preferred methods for learning travel routes were collected.

Table 6.1.: Participant demographics and experience with 2D user interfaces (P1-P9).

Users	Age	Gender	VI Type (VA)	2D UI Exp.	Route Learning Method
P1	30 – 45	female	VI (< 6/60)	no	VAG App, DB Navi
P2	30 – 45	female	VI (< 6/60)	no	VAG App, DB Navi
P3	18 – 30	male	VI (< 6/60)	no	Google Maps
P4	18 – 30	female	VI (< 6/60)	no	Google Maps
P5	18 – 30	male	VI (< 6/60)	no	Google Maps
P6	30 – 45	male	CB (< 3/60)	yes	Apple Maps
P7	18 – 30	male	CB (< 3/60)	no	BlindSquare App
P8	18 – 30	male	CB (< 3/60)	no	-
P9	18 – 30	male	CB (< 3/60)	yes	Google Maps

Visual acuity (VA) levels defined by the WHO [3].

Materials - Graphics

This study used solely one audio-tactile network map to assist users in learning and exploring the Tap-to-Hear Map-Route exploration user interface, the Nuremberg metro network map (Figure 6.4). All participants reside in Nuremberg and are familiar with the public transportation network, providing a solid baseline understanding of the map's structure and motivation to engage with the UI. In addition to this familiarity, the Nuremberg map was chosen for its relative simplicity, featuring only three underground lines, with the chosen travel route involving only two of them (starting on U2 and switching to U1 later). Only the main underground lines were included, excluding bus services and other transportation services. The study utilized the real-world-based Nuremberg metro map because it offers a realistic evaluation environment, avoiding oversimplified designs that might artificially enhance interface performance.

The map was created with the open-source tool Inkscape, following the ProBlind database layout in SVG format. The travel route width was increased to three times its original size relative to the other lines on the network map, enhancing its prominence for tactile recognition by users. The map title annotations include the names of the underground stations, while the descriptive data provides detailed information about each station's connectivity and nearby points of interest. For instance, the description highlights the number of transfer options available at a station and notable landmarks in its surroundings, such as proximity to a central park or the city centre square.

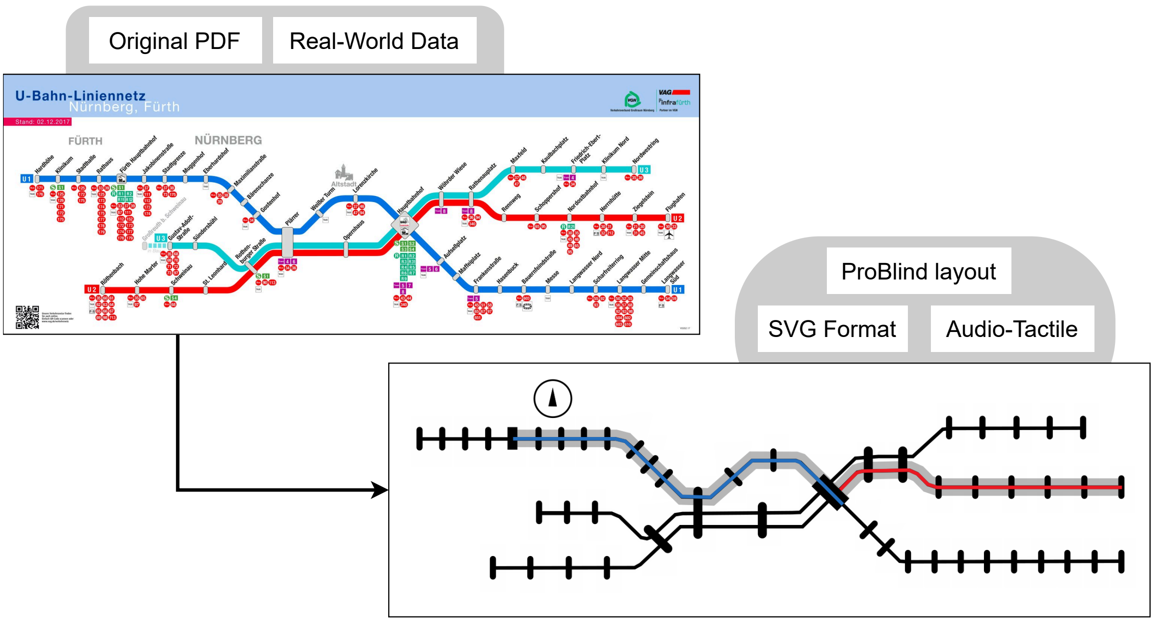

Figure 6.4.: The Nuremberg metro network map adapted from the official data provided (2021) by VAG (Verkehrs-Aktiengesellschaft Nürnberg). The chosen travel route is highlighted in the SVG format, with different colours representing the distinct underground lines followed along the route.

6.2.1. Experimental Setup

Each participant interacted exclusively with the tap-to-hear UI on the Nuremberg metro network map during a 60-minute individual session. Figure 6.5 outlines the experimental procedure, illustrating its distinct phases for clarity and comprehension.

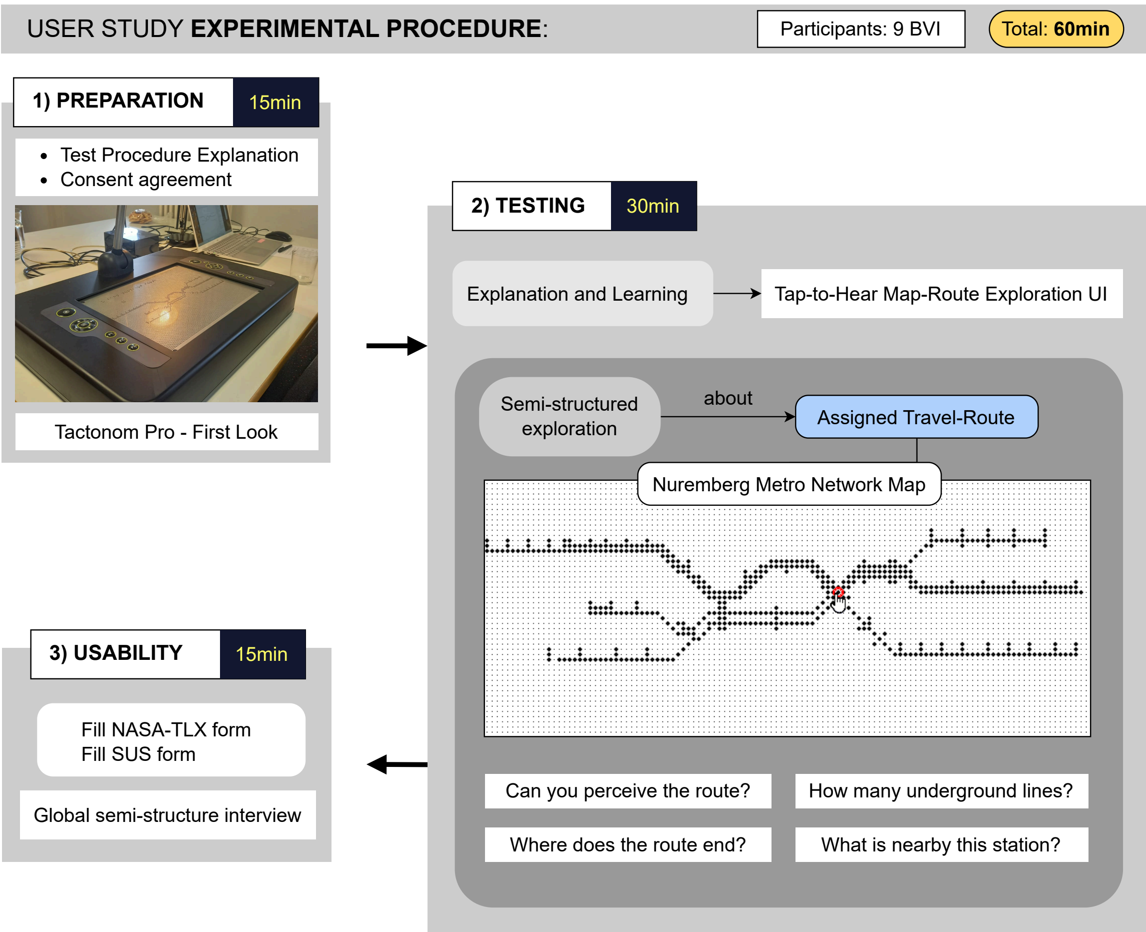

Figure 6.5.: Tap-to-Hear Map-Route Exploration: Experimental Procedure

Study Procedure - Preparation

At the start of the study, participants were briefed on the purpose and procedures. They then provided consent, either by signing a form or giving verbal agreement, which was audio recorded. They were also reminded of their right to withdraw from the study at any point without explanation. Next, participants spent 15 minutes familiarising themselves with the Tactonom Pro device (see Section 3.1.2), including its dimensions, camera-based finger detection, side UI buttons, and page-reloading system. Given the limited session duration (60 minutes), there was not enough time for participants to explore other Tactonom Pro features, as the extended focus would likely lead to fatigue.

Study Procedure - Testing

After receiving instructions and confirming their understanding of the protocol, participants moved on to the testing phase, engaging with the tap-to-hear exploration UI on the Nuremberg metro network map. They were instructed to explore and learn a predefined travel route with 20 stops, covering two underground lines (one transfer station). During exploration, participants were prompted with questions such as “Where does the route end?” and “Can you switch to another line from your current station?” to assess the interface’s strengths and weaknesses while encouraging users to consider how they could learn the route. Such exploration was semi-structured, allowing participants some flexibility to explore other elements of the network map while still focusing on the main route. This method aimed at facilitating broader feedback without limiting interaction. Such methodology also aimed at identifying improvements in data presentation and evaluating the interface’s scalability for more complex network maps.

Study Procedure - Usability

At the end of the study, participants filled out the NASA-TLX [132] and SUS [60] questionnaires, focusing on their interaction with the tap-to-hear interface. Following this, a semi-structured interview was conducted to assess user experience and identify challenges, including ratings of each UI’s utility for understanding travel routes and individual feature ratings of the immersive UI. This format enabled the experimenter to delve into participant observations alongside the standard question set.

Additional information regarding the study tasks is available in Appendix B.3.

Data Analysis Methodology

The study combined quantitative measures (NASA-TLX [132] for cognitive load and SUS [60] for user satisfaction) with qualitative insights from interviews. Questionnaires were evaluated using normalised scores, while subjective data from interviews were analysed using descriptive statistics and thematic analysis. Participant feedback was labelled with unique identifiers and categorised by visual impairment type (CB: congenitally blind, VI: visually impaired, e.g., P3, VI).

6.2.2. Results

The analysis aimed to assess the significance of the tap-to-hear UI for learning routes in network maps, identifying its limitations and potential for improvement. Section 6.2.2.1 examines usability factors such as cognitive load, user satisfaction, and utility ratings, while Section 6.2.2.2 discusses participant feedback on the UI's scalability and growth potential.

Usability Analysis

Cognitive load was assessed using normalised NASA-TLX scores (0-100 scale), where lower values indicate reduced cognitive load. The mean NASA-TLX score was 16.76 ± 13.70 (Figure 6.6 - left plot). User satisfaction was measured with normalized SUS scores on a 0-100 scale, with higher scores reflecting greater usability. The mean SUS score reported by participants was 71.67 ± 17.90 (Figure 6.6 - left plot), which, while not low, falls below the threshold of high usability (<80), as indicated by previous research [23, 258]. During semi-structured interviews, participants rated the utility of the tap-to-hear UI for learning travel routes on a 1–5 scale (1: not helpful, 5: very useful). The mean utility rating was 2.67 ± 1.12 (Figure 6.6 - right plot). Participants substantiated these findings with a mix of positive feedback and frustration regarding the tap-to-hear UI, as reflected in comments such as "I need to learn a lot of things in the beginning because this is all new to me" – (P8, CB), "It helps me, but it is frustrating; makes me lose concentration when moving the zoom view" – (P6, CB), and "This is already good, but I still need some time to learn the entire route" – (P1, VI).

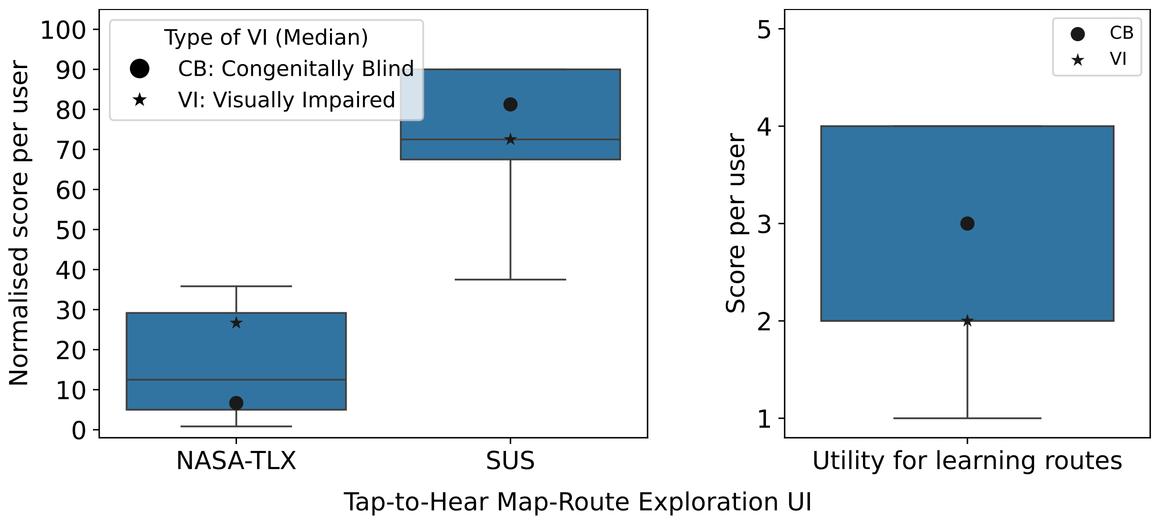

Figure 6.6.: Usability analysis - Tap-to-Hear Exploration UI. The left plot shows the distribution of NASA-TLX and SUS scores. The right plot represents users' utility ratings for learning travel routes. Although no comparative analysis was conducted, the figure highlights the distinction between visual impairment types, with boxplot medians marked by circles for CB and stars for VI.

UI Growth and Expansion

Through thematic analysis of user comments and reactions during the experiment, various suggestions for improving the tap-to-hear UI for learning routes in network maps were identified. Participants emphasised the need for greater flexibility in the information provided: "Customisation is essential, where I could filter the information I am interested in, e.g., stations with ATMs" – (P2, VI), "I would like to have information about nearby markets or shopping centres." – (P8, CB). Suggestions also focused on making better use of audio: "Using more sounds would be better" – (P5, VI), "Associate background sounds with areas you are close to, like birds singing to indicate a park is nearby" – (P9, CB).

During semi-structured interviews, participants identified different contexts in which the tap-to-hear exploration UI could be applied. All suggestions were focused on navigation and geographical scenarios, as reflected in comments such as: "Scalable to city maps to learn all the stores in a city, or indoor plans of a doctor's office" – (P8, CB), "Definitely for anything related to geography" – (P4, VI), "On city maps, to explore a route to the hotel when going on holiday" – (P7, CB), and "Station maps with open street map data could be useful to find toilets or identify stairs and escalators" – (P2, VI). Even on-site navigation was considered: "It would be great to have a miniaturised device in hand" – (P3, VI).

6.2.3. Discussion

Overall, participants had a generally positive experience with the tap-to-hear UI for learning routes in network maps, as reflected in moderate NASA-TLX and SUS scores. However, they also offered constructive criticism, suggesting that while the interface is promising, it still falls short of fully addressing the challenge. A need for more comprehensive information representation and a faster approach was expressed: "I would like to have information about nearby markets or shopping centres" – (P8, CB), and "This is already good, but I still need some time to learn the entire route" – (P1, VI). This sentiment was reflected in the mean usability score of 2.67 out of 5, indicating that while participants were satisfied, they saw room for improvement and further innovation: "Associate background sounds with areas you are close to, like birds singing to indicate a park is nearby" – (P9, CB).

It is worth noting the tap-to-hear UI was tested on a small-scale network map (Nuremberg metro), and more complex scenarios were not considered. Time constraints during the study restricted the exploration of additional network maps and features, especially when interacting with new technologies like 2D refreshable tactile pin displays. Explaining new technology and innovative user interfaces is challenging and time-consuming. This highlights the importance of well-designed user studies that balance robust evaluation with clear instructions (user tasks).

Further research, including more extended studies and realistic, real-world scenarios, is needed to fully assess UI solutions for helping BVI individuals learn complex routes. User insights and improvement suggestions from this study led to the development of the immersive travel-map exploration UI (Figure 6.2).

6.3. LEARNING THROUGH IMMERSIVE MAP-ROUTE EXPLORATION

As part of the human-centred design methodology adopted in this dissertation, a user study was conducted to validate and evaluate the performance of the immersive map-route exploration UI (figure 6.2). This **immersive** UI was analysed against the developed tap-to-hear map-route exploration UI (figure 6.1) to benchmark its performance and assess its capabilities. The study concentrated on investigating how such UIs assist individuals with BVI in learning and exploring complex travel routes on large metro network maps. In line with the broader objectives of this research, the study not only validated the interface but also explored additional factors, including network map complexity, variations in visual impairment, and the scalability of the UI.

Participants

The study included 12 BVI participants (three females, nine males; Table 6.2) recruited through local educational centres for the blind in Nürnberg (BBS). Interested individuals received study details and participated if they reported a medical diagnosis of blindness or visual impairment, as visual acuity was not directly measured. Exclusion criteria included being under 18, substance abuse, and medical conditions affecting cognition, touch, hearing, communication, or motor skills. The KIT University ethics committee approved the study, and all participants provided informed consent. Self-reports categorised participants into two equally balanced groups, six congenitally blind (CB) and six visually impaired (VI), providing an optimal distribution for robust comparative analysis between VI types. 7 of the 12 participants took part in the prior study on the tap-to-hear UI (Sec. 6.2).

Table 6.2.: Participant demographics and experience with 2D user interfaces (P1-P12).

Users	Age	Gender	VI Type (VA)	2D UI Exp.	Route Learning	Prior
P1	18 – 30	male	CB (< 3/60)	no	DB Navigator	no
P2	18 – 30	female	VI (< 6/60)	no	Apple Maps, DB Nav.	no
P3	18 – 30	male	CB (< 3/60)	yes	Google Maps	yes
P4	30 – 45	male	CB (< 3/60)	no	-	no
P5	30 – 45	female	VI (< 6/60)	no	VAG App, DB Nav.	yes
P6	18 – 30	male	VI (< 6/60)	no	Google Maps	yes
P7	18 – 30	female	VI (< 6/60)	no	Google Maps	yes
P8	18 – 30	male	VI (< 6/60)	no	Google Maps	yes
P9	30 – 45	male	VI (< 6/60)	DotPad: A.18	Google, Tactile Maps	no
P10	30 – 45	male	CB (< 3/60)	Old Tactonom	Apple Maps	no
P11	18 – 30	male	CB (< 3/60)	no	-	yes
P12	18 – 30	male	CB (< 3/60)	no	BlindSquare App	yes

Visual acuity (VA) levels defined by the WHO [3].

Materials - Graphics

This study used a total of three audio-tactile network maps: one for understanding the exploration UIs and two for testing them. To assist users in learning the exploration user interfaces, the Nuremberg metro network map was selected (Figure 6.4). All participants reside in Nuremberg and are familiar with public transportation, providing a solid baseline understanding of the map's structure and motivation to engage with the interfaces. Notably, 7 of the 12 participants had already interacted with this map in a previous study, further facilitating their learning of the UI. The Nuremberg map was also chosen for its relative simplicity, featuring only three underground lines on its network, with the chosen travel route involving only two of them (starting on U2 and switching to U1 later). The Paris and Madrid metro network maps were selected for testing the user interfaces primarily due to their complexity, with both networks featuring 14 underground lines each (Figure 6.7). These maps were also chosen because they were unfamiliar to the participants, ensuring that prior knowledge did not influence their performance. Only the main underground lines were included, excluding bus services. The selected travel route for Paris involved three underground lines, while the Madrid route involved four underground lines.

All metro network maps used in this study are based on real-world data obtained from publicly available metro network maps published by the respective transport authorities. Using this data, the maps were created with the open-source tool Inkscape, following the ProBlind database layout in SVG format. The selected travel routes, also based on real-world data, were designed for the study and correspond to operational routes within the respective metro systems. For the immersive UI, a JSON file based on its XSD schema was created to link each travel route to its corresponding SVG network map. For the tap-to-hear UI, the travel route width was scaled up to three times its original size compared to the other lines on the network map. The map titles display the names of underground stations, while the corresponding annotations provide detailed descriptions of each station's connectivity and surrounding points of interest. These descriptions include information on available transfer options and highlight significant nearby landmarks, such as a football stadium, a university, or ongoing construction work.

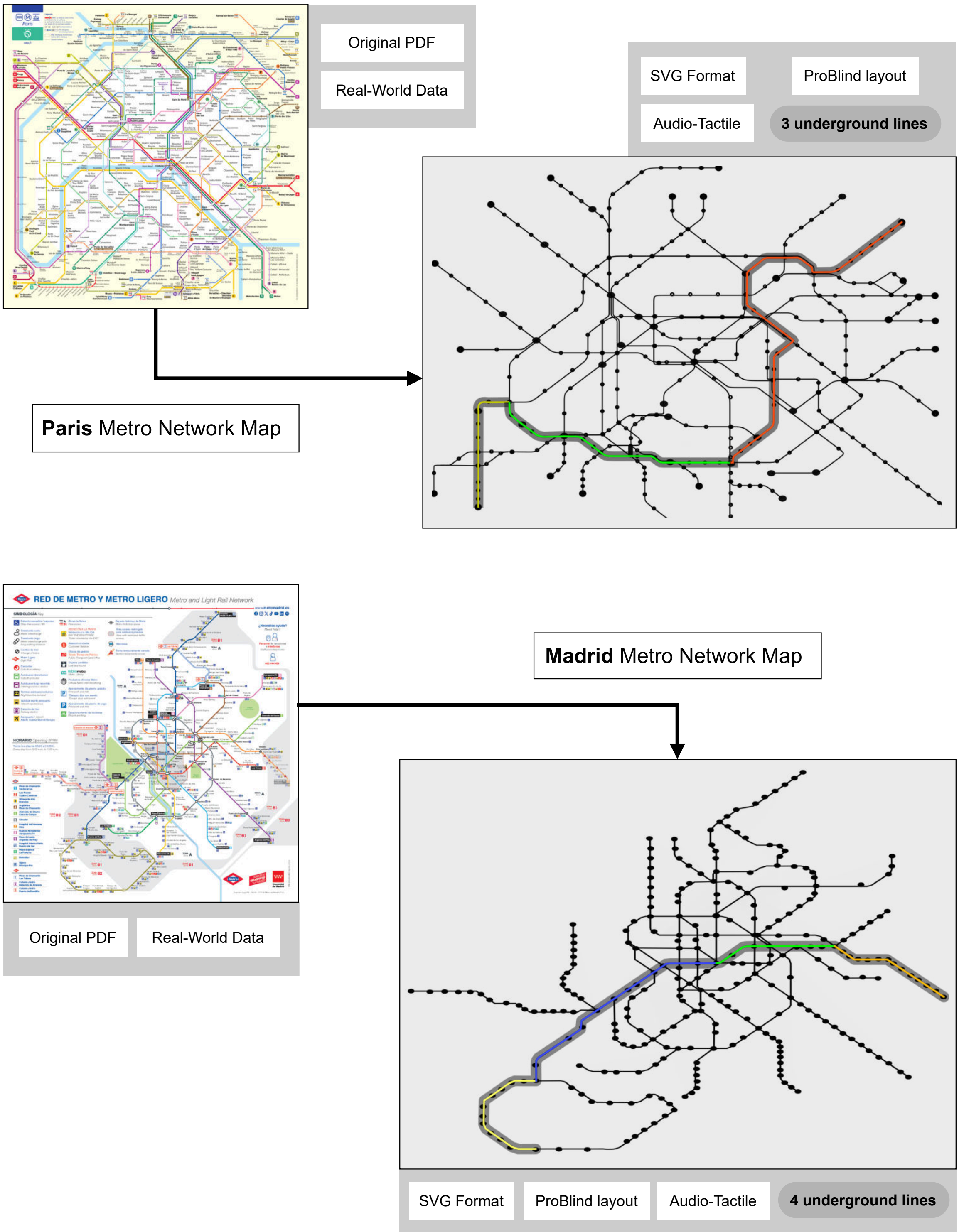

Figure 6.7.: The Paris and Madrid metro network maps adapted from official data provided by RATP (Régie Autonome des Transports Parisiens) and CRTM (Consorcio Regional de Transportes de Madrid), respectively. The chosen travel routes are highlighted in the SVG format, with different colours representing the distinct underground lines followed along the route.

6.3.1. Experimental Setup

A within-subjects design was employed, where each participant interacted with both user interfaces (immersive and tap-to-hear). To control for order effects, a counterbalanced design was implemented, systematically varying the combinations of user interfaces and network maps (Paris and Madrid). With two UIs and two maps, four unique order combinations (UI1-Map1 → UI2-Map2, UI1-Map2 → UI2-Map1, UI2-Map1 → UI1-Map2, and UI2-Map2 → UI1-Map1) were evenly distributed across the 12 participants, ensuring each order was tested by three participants. This counterbalanced approach minimized biases from order effects, ensured even distribution of all combinations, and enhanced the reliability of the comparative analysis. The distribution of VI types across UI orders was counterbalanced, with 3 VI and 3 CB participants testing UI1 first and the remaining 6 testing UI2 first, ensuring a balanced comparison between groups. The tests were conducted individually in a single 90-minute session for each participant. Figure 6.8 illustrates the step-by-step progression of the experimental procedure, ensuring clarity and enhancing comprehension of the distinct phases involved.

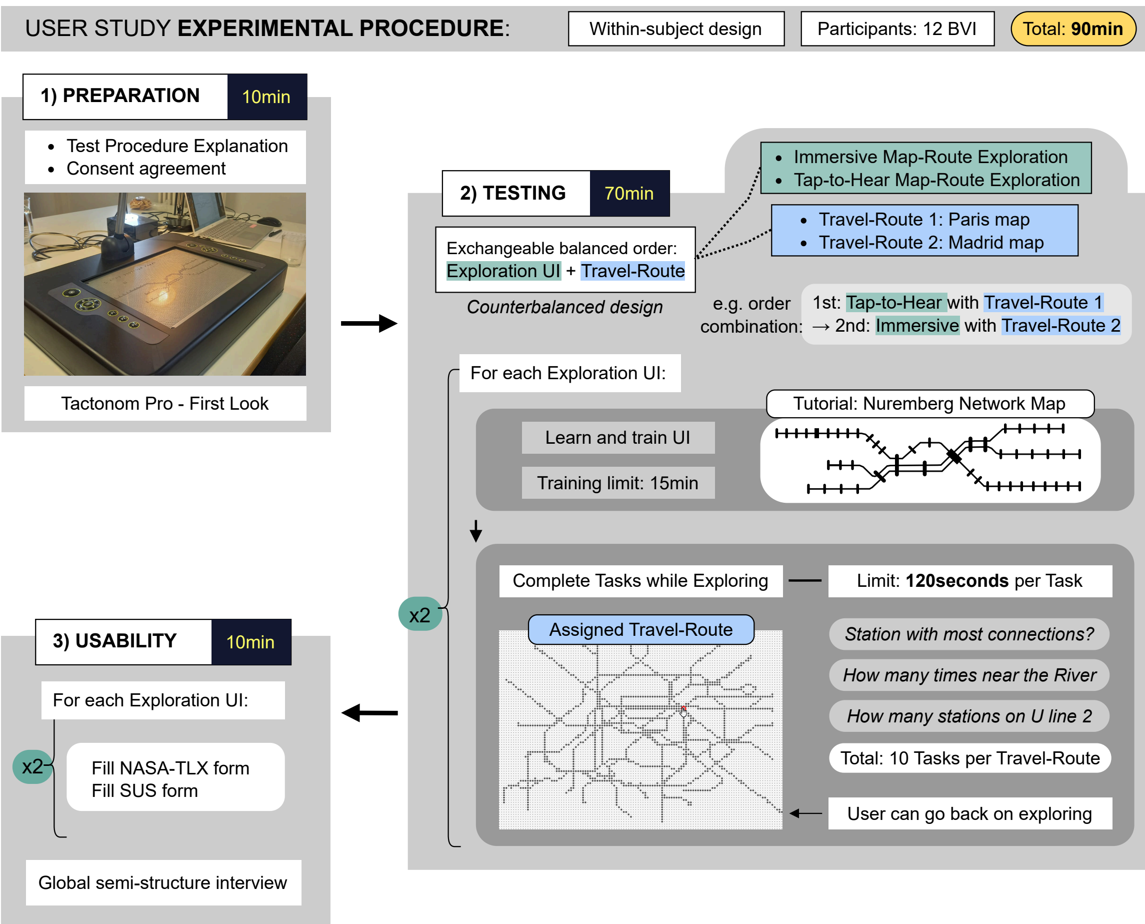

Figure 6.8.: Immersive Map-Route Exploration: Experimental Procedure

Study Procedure - Preparation

At the beginning of the study, participants received a detailed explanation of the study's purpose and procedures. They were then asked to provide their consent either by signing a consent form or giving verbal agreement, which was audio recorded. Participants were informed of their right to quit the experiment at any time without providing a reason. Following this, participants familiarised themselves with the Tactonom Pro device (see Section 3.1.2), including its dimensions, camera-based finger detection, side UI buttons, and page-reloading system. This familiarisation phase lasted 10 minutes. Due to the 90-minute session length, there was insufficient time for participants to explore other applications of the Tactonom Pro, as maintaining attention beyond this duration would likely lead to fatigue.

Study Procedure - Testing

After receiving instructions and confirming their understanding of the experimental protocol, participants progressed to the testing phase, where they interacted with the exploration UIs. This phase consisted of two identical sub-sessions, each dedicated to one of the UIs, ensuring that participants explored both sequentially.

Each sub-session began with a 15-minute familiarisation period using the Nuremberg network map (Figure 6.4) to allow participants to learn the UI's functionality. Although 15 minutes may appear lengthy compared to other user studies in this dissertation, it was deemed appropriate given the complexity of the UIs and the novel nature of the Tactonom Pro device. The UIs involved multiple elements, and even with the relatively simple Nuremberg map, users needed sufficient time to familiarise themselves with the interface. Additionally, the page-refreshing process on the Tactonom Pro (10 seconds per page) extended the overall duration of the familiarisation phase. Following this, participants completed a 20-minute testing session for each UI, performing 10 tasks to assess their understanding of the assigned route (Paris or Madrid - Figure 6.7). Each task had a 120-second time limit, during which participants used the assigned UI to explore the network map and complete the task. Tasks were divided into two categories: overview tasks, which assess the user's grasp of the route's general structure, and detail tasks, which evaluate the user's ability to go deep and understand specific segments of the route. Overview tasks included questions such as '*How many times does the entire route pass close to the river?*' or '*Which underground lines are included in the entire route?*' Detail tasks focused on specific segments, such as '*How many stations are on the first underground line of the route?*' or '*Which stations on underground line 3 have undergoing construction?*'. Each travel route included four overview tasks and six detail tasks. Task outcomes were evaluated for effectiveness after each attempt, and task duration was timed. Participants could skip a task, which would be recorded as incomplete and assigned the entire 120-second duration. The task sequence was consistent for all participants.

Study Procedure - Usability

At the conclusion of the study, participants completed the NASA-TLX [132] and SUS [60] questionnaires to assess each exploration user interface. Subsequently, they took part in a semi-structured interview to evaluate their user experience, discussing topics such as their preferred interface and reasons for their choice, ratings of individual immersive UI components, the perceived complexity of the network maps, potential applications of the interfaces in various contexts, and their effectiveness in assisting blind or visually impaired users with 2D refreshable tactile displays. The semi-structured format allowed the experimenter to explore observations shared by participants in addition to the standard questions posed to all participants.

Additional information regarding the study tasks is available in Appendix B.3.

Data Analysis Methodology

A mixed-methods approach was employed, integrating both quantitative and qualitative data, including interviews. Analyses focused on effectiveness (tasks completed correctly), efficiency (trial duration, NASA-TLX score [132]), and user satisfaction (SUS score [60]), with these measures serving as the dependent variables. Since all analyses involved comparisons between two groups and the normality of the data was not tested, non-parametric Wilcoxon signed-rank tests [320] were employed for statistical analysis. Questionnaires (NASA-TLX and SUS) were evaluated using normalised scores, while subjective data from interviews were analysed using descriptive statistics and thematic analysis. Participant comments were paired with identifiers and visual impairment types (CB: congenitally blind, VI: visually impaired, e.g., P7, CB).

6.3.2. Results

The analysis primarily focused on comparing the user interfaces in terms of effectiveness, efficiency, and user satisfaction (section: 6.3.2.1). Leveraging the counterbalanced design, additional investigations examined variations across network maps (Paris and Madrid metro lines - section: 6.3.2.2) and types of visual impairment (CB and VI - section: 6.3.2.3). Further analysis focused on investigating the individual features that make the immersive user interface unique (section: 6.3.2.4) and assessing its potential to scale across different contexts and applications (section: 6.3.2.5).

Figures in this section include specific markers and outliers to enhance the clarity of the data presentation. In the boxplots, the black markers represent the medians for each subgroup of visual impairment type: circles denote individuals with CB (Congenitally Blind), and stars indicate individuals with VI (Visually Impaired). Additionally, outliers in the plots are marked as grey diamonds.

User Interface Analysis (Tap-to-Hear vs Immersive)

To assess UI effectiveness, the distribution of tasks completed correctly for each strategy was examined. The mean number of tasks completed correctly per user was 3.08 ± 1.83 with the tap-to-hear UI and 9.25 ± 0.75 with the immersive UI (Figure 6.9 - left plot). A two-tailed Wilcoxon signed-rank test yielded $W = 0.0$ and $p \approx 0.0005$, indicating a significant difference ($\alpha < 0.05$). The null hypothesis was rejected, suggesting that the immersive UI was significantly more effective for learning and exploring routes in network maps compared to the tap-to-hear UI.

To investigate whether the immersive UI's effectiveness differed significantly from the tap-to-hear UI across specific task types, the overview and detail tasks were analysed individually. (Figure 6.9 - right plot). Out of 4 overview tasks, the mean number of overview tasks completed correctly per user was 0.92 ± 0.67 with the tap-to-hear UI and 3.92 ± 0.29 with the immersive UI. Out of 6 detail tasks, the mean number of detail tasks completed correctly per user was 2.17 ± 1.47 with the tap-to-hear UI and 5.33 ± 0.65 with the immersive UI. Two-tailed Wilcoxon signed-rank tests confirmed significant differences ($\alpha < 0.05$) between the UIs for both overview tasks ($W = 0.0$, $p < 0.001$) and detail tasks ($W = 0.0$, $p < 0.001$) demonstrating that the immersive UI significantly outperformed the tap-to-hear UI in terms of effectiveness for both task types individually.

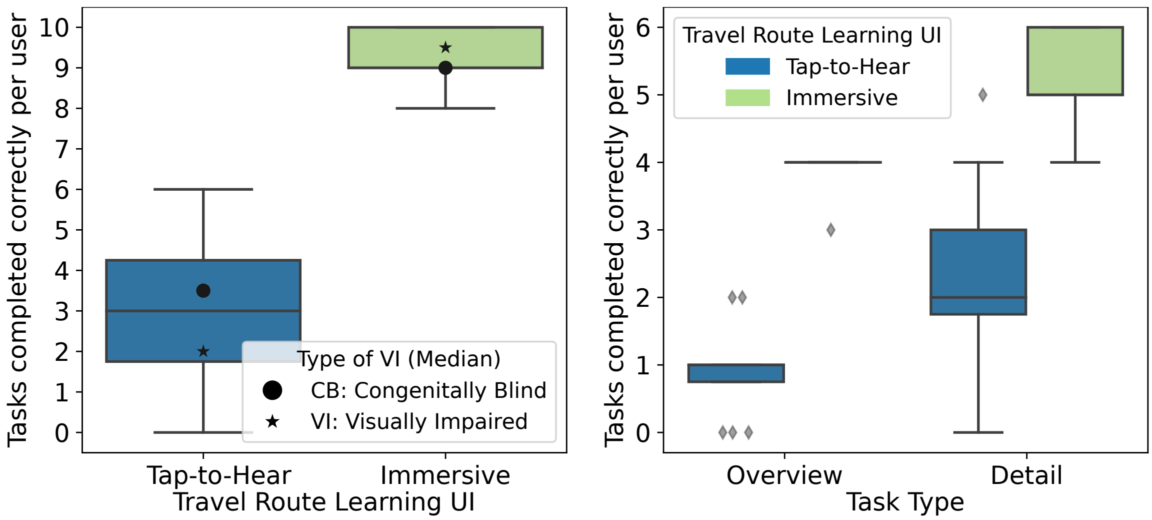

Figure 6.9.: Effectiveness analysis - task completion. The left plot shows tasks completed correctly per participant for each UI (12 samples per UI). The right plot shows the distribution for each task type (overview and detail) across all user interfaces. Boxplots show the distribution of tasks completed per participant, with medians represented as solid lines.

User interface efficiency was evaluated by measuring participants' duration (in seconds) to complete all tasks (Figure 6.10 - left plot). The mean duration taken per user to complete all tasks was 986.17 ± 133.20 seconds with the tap-to-hear UI and 742.92 ± 180.59 with the immersive UI. A two-tailed Wilcoxon signed-rank test confirmed significant differences ($\alpha < 0.05$) between the UIs ($W = 0.0$, $p < 0.001$), indicating a rejection of the null hypothesis. This suggests that users took significantly less time to complete the tasks with the immersive map-route exploration UI compared to the tap-to-hear map-route exploration UI.

Cognitive load was assessed using normalised NASA-TLX scores to evaluate user efficiency (Figure 6.10 - right plot). The mean NASA-TLX score was 38.61±18.53 for the tap-to-hear UI and 12.01 ± 8.89 for the immersive UI. A two-tailed Wilcoxon signed-rank test confirmed significant differences ($\alpha < 0.05$) between the UIs ($W = 0.0$, $p < 0.001$), indicating a rejection of the null hypothesis. These results suggest that users perceived the immersive map-route exploration UI as imposing significantly less cognitive load than the tap-to-hear map-route exploration UI.

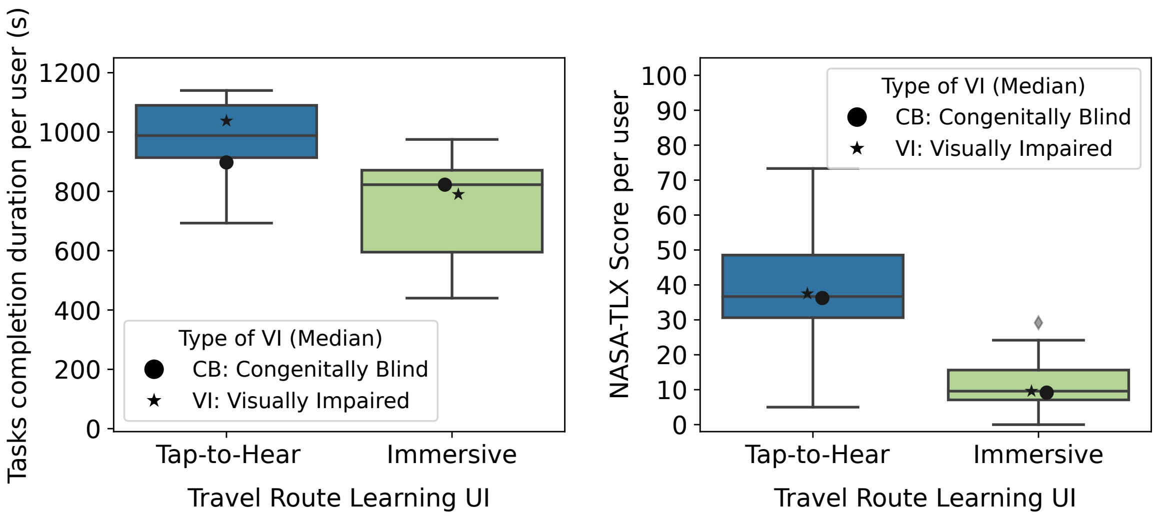

Figure 6.10.: Efficiency analysis - tasks completion duration and NASA-TLX Score. The left plot shows the distribution of total duration (in seconds) taken by participants to complete all tasks per UI. The right plot shows the distribution of participants´ NASA-TLX scores per UI.

To assess user satisfaction, normalized SUS scores (0–100 scale) were analysed, with higher scores indicating greater satisfaction. Participants reported a mean SUS score of 55.63 ± 18.98 for the tap-to-hear UI and 82.08 ± 10.91 for the immersive UI (Figure 6.11 - left plot). A two-tailed Wilcoxon signed-rank test yielded $W = 1.0$ and $p < 0.001$, indicating a significant difference in SUS scores between the UIs ($\alpha < 0.05$). These findings highlight the higher satisfaction with the immersive UI compared to the tap-to-hear UI for learning and exploring routes on 2D refreshable tactile pin displays.

Participants rated each UI on a 1–5 scale for its usefulness in understanding routes on 2D refreshable tactile pin displays. The tap-to-hear UI received a mean utility rating of 2.42 ± 0.90, while the immersive UI scored 4.58 ± 0.67 (Figure 6.11 - right plot). A Wilcoxon signed-rank test yielded W = 0.0 and a p-value of < 0.001, indicating a significant difference in users' utility rating between the UIs ($\alpha < 0.05$). Qualitative feedback from participants substantiated these findings, expressing frustration and highlighting dissatisfaction with the tap-to-hear UI, as reflected in comments such as "I do not have the time to find this! It is too difficult!" – (P7, VI), "This is definitely not good enough!" – (P6, VI), "I want to try more! It is fun but also frustrating. 2 minutes is not enough." – (P11, CB), and "It was really annoying! I was trying to go slow but still missed important information." – (P12, CB). In contrast, the immersive UI received praise, "It was very quick to learn with the immersive UI." – (P1, CB), "The second UI (immersive UI) can help me a lot and uses things I never learned at school." – (P2, VI), "Even with too much information I am able to follow the route line with it." – (P9, VI), and "It is really fun with the immersive UI, and the fun really helps." – (P12, CB). These results also emphasise the higher satisfaction associated with using the immersive UI compared to the tap-to-hear UI when learning travel routes on 2D refreshable tactile pin displays.

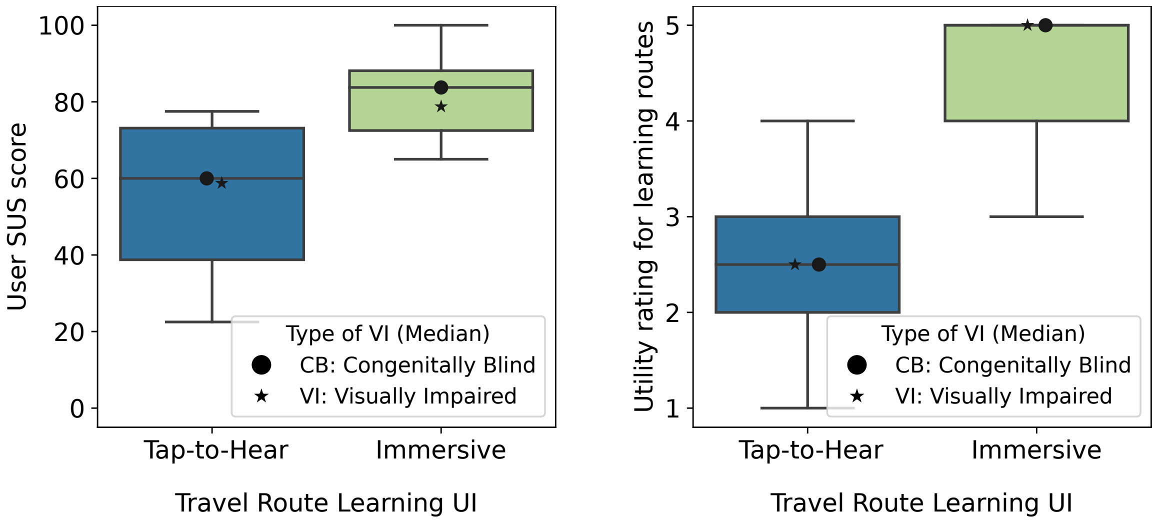

Figure 6.11.: User satisfaction analysis - SUS score and Utility rating. The left plot shows the distribution of participants' SUS normalised scores per UI. The right plot shows the distribution of participants´ utility ratings for learning routes per UI.

Network Map Analysis (Paris vs Madrid)

In this user study, two complex network maps, the Paris and Madrid metro networks, were employed. Each featured a distinct, challenging route for participants to learn. An analysis was conducted to assess effectiveness, efficiency, and perceived difficulty across the two maps, aiming to determine whether both network maps exhibited comparable complexity or if discrepancies existed in the data that could introduce imbalance to the study. The Nuremberg network map, although not used for task completion, was also included in the perceived difficulty analysis for comparison, given the available data.

In terms of effectiveness, the distribution of correctly completed tasks for each network map was analysed. The mean number of tasks completed correctly per user was 6.50 ± 3.09 on the Paris map and 5.83 ± 3.86 on the Madrid map (Figure 6.12 - left plot). A two-tailed Wilcoxon signed-rank test was performed, yielding a Wilcoxon statistic of 29.5 and a p-value of 0.52. Since the p-value exceeds the significance level of $\alpha = 0.05$, the null hypothesis isn't rejected, indicating no significant difference in the number of tasks completed correctly between the two network maps.

Regarding efficiency, the mean duration per user to complete all tasks was 879.50 ± 117.50 for the Paris map and 849.58 ± 261.41 for the Madrid map (Figure 6.12 - right plot). A two-tailed Wilcoxon signed-rank test yielded a Wilcoxon statistic of 35.0 and a p-value of 0.79. Given that the p-value is bigger than $\alpha = 0.05$, the null hypothesis is retained, suggesting no significant difference in task completion duration between the two network maps.

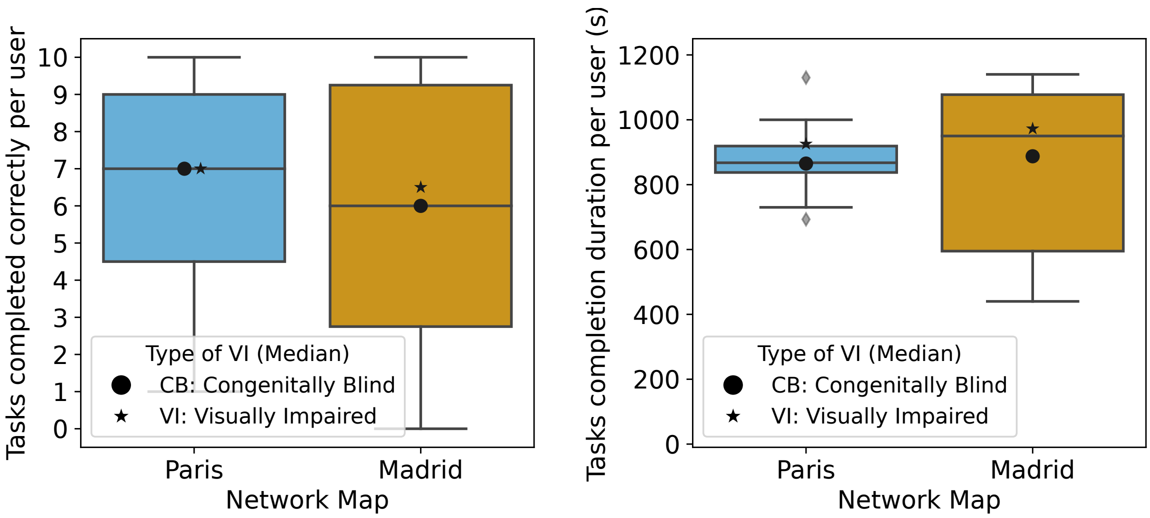

Figure 6.12.: Network map analysis - Effectiveness and efficiency. The left plot shows the distribution of tasks completed correctly per participant for each network map. The right plot illustrates the distribution of total duration (in seconds) taken by participants to complete all tasks for each network map.

Perceived difficulty was assessed by asking participants to rate each network map (including the Nuremberg network map) on a scale from 1 (easy) to 5 (very hard). The mean difficulty ratings were 3.00 ± 1.04 for Paris, 3.33 ± 0.98 for Madrid, and 1.25 ± 0.45 for Nuremberg (Figure 6.13 - left plot). A Friedman test showed a significant difference in difficulty across maps ($W = 18.82$, $p < 0.0001$). Post-hoc pairwise Wilcoxon tests with Bonferroni correction ($\alpha = 0.05/3 = 0.0167$) revealed no significant difference between Paris and Madrid ($W = 4.5$, $p = 0.41$), but significant differences between Paris and Nuremberg ($W = 0.0$, $p = 0.0046$) and Madrid and Nuremberg ($W = 0.0$, $p = 0.0005$), suggesting that both Paris and Madrid maps were perceived as more challenging than Nuremberg.

Since no significant difference was found in the perceived difficulty of the network maps themselves, an additional analysis was conducted to investigate whether the type of user interface affected participants' difficulty ratings of the maps. The mean map difficulty rating for the tap-to-hear UI was 3.58 ± 1.00, while the mean rating for the immersive UI was 2.75 ± 0.87 (Figure 6.13 - right plot). A two-tailed Wilcoxon signed-rank test was performed to compare the ratings between the two UIs, resulting in a Wilcoxon statistic of 0.0 and a p-value of 0.041. With a significance threshold of $\alpha = 0.05$, this result indicates a statistically significant difference, suggesting that participants perceived the Paris and Madrid maps as less difficult when using the immersive UI compared to the tap-to-hear UI. Participant feedback corroborated these findings, highlighting the complexity of network maps when using the tap-to-hear UI, as reflected in comments such as "It was confusing when I had multiple lines. I did not know which line to follow." – (P3, CB) and "5 is not enough! I would give it a 10!" – (P8, VI) (when evaluating the map's difficulty on a scale of 1 to 5).

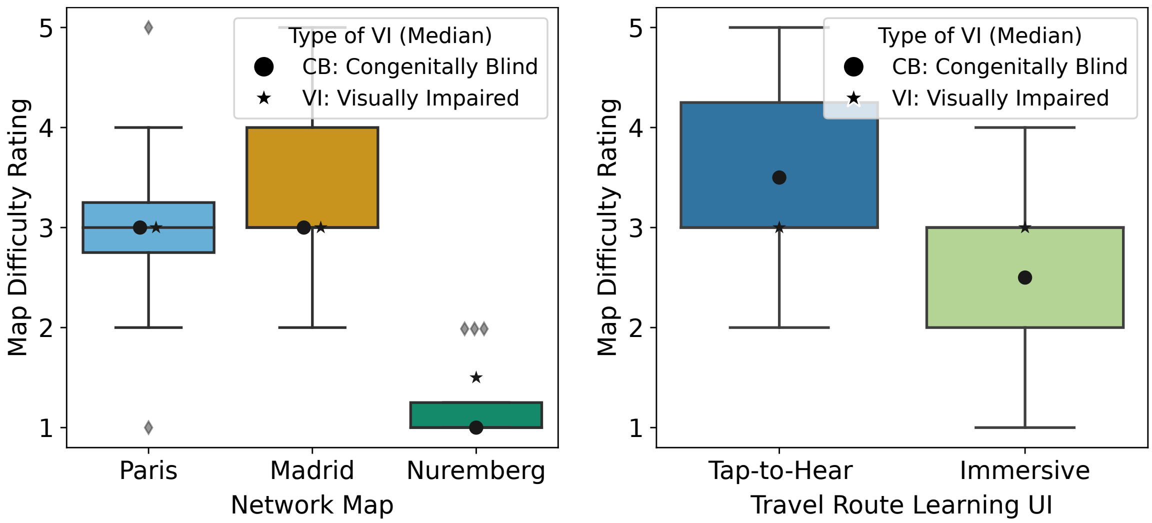

Figure 6.13.: Network maps perceived difficulty rating. The left plot shows the distribution of participants' difficulty ratings for learning routes on each network map (Paris, Madrid, and Nuremberg). The right plot illustrates map difficulty ratings grouped by the user interface used to interact with the map (Tap-to-Hear vs. Immersive).

Visual Impairment Variation Analysis

The analysis aimed to determine whether the type of visual impairment affects efficiency, effectiveness, and user satisfaction when using the immersive UI. The participant group was balanced, with six individuals having visual impairments (VI) and six congenitally blind (CB). UI order was evenly distributed across the two groups, ensuring that any observed effects were due to the type of visual impairment rather than the UI order, allowing for valid statistical analysis.

No significant differences (using two-tailed Wilcoxon signed-rank tests) were found between VI and CB individuals across all measures when using the immersive UI (Figure 6.14). Task completion accuracy was similar for both groups, with the VI group achieving a mean of 9.5 ± 0.55 tasks completed correctly and the CB group 9.0 ± 0.89 tasks ($W = 2.0$, $p = 0.257$). Task duration also showed no significant difference, with the VI group completing all tasks on average in 760 ± 174.18 seconds and the CB group in 725.83 ± 201.75 seconds ($W = 10.0$, $p = 1.0$). The NASA-TLX normalised score was 14.03 ± 10.28 for VI and 9.998 ± 7.64 for CB, with no significant difference ($W = 7.0$, $p = 0.563$). Similarly, SUS scores were 80.0 ± 13.13 for VI and 84.17 ± 8.90 for CB, showing no significant difference ($W = 7.0$, $p = 0.563$).

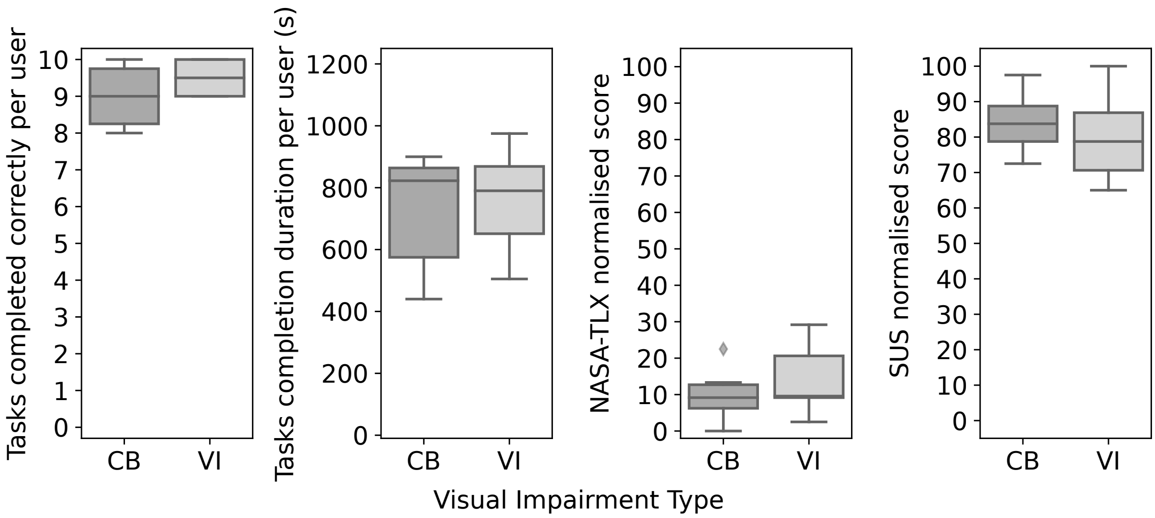

Figure 6.14.: Visual impairment variation analysis - Immersive UI. The leftmost plot shows the distribution of tasks completed correctly per participant on the immersive UI. The left-centre plot illustrates the distribution of total duration (in seconds) taken by users to complete all tasks with the immersive UI. The right-centre plot shows the distribution of participants' NASA-TLX normalised scores. The rightmost plot shows the distribution of participants' SUS normalised scores. All distributions are grouped by visual impairment type.

Examination of Immersive UI Components

Beyond the direct comparison of user interfaces, the analysis also focused on identifying the most notable components of the immersive UI and assessing these individually. During the semi-structured interviews, participants rated the usefulness of each characteristic of the immersive UI for understanding and learning routes on a scale from 1 (not useful) to 5 (very useful). Although the route-only view rendering feature is shared with tap-to-hear UI, it is part of the immersive UI and was included in this analysis. The mean usefulness ratings (± standard deviations) for the features were as follows: line tracing (4.83 ± 0.39), node connections (4.50 ± 1.00), POI beacons (4.67 ± 0.65), route phase split (4.83 ± 0.39), sound filtering (3.92 ± 0.90), and route-only rendering (4.00 ± 0.95). A Friedman test revealed a statistically significant difference in the usefulness ratings among the immersive UI features (test statistic: 21.56, $p = 0.0006$). Post-hoc pairwise comparisons using two-tailed Wilcoxon signed-rank tests were conducted to examine the differences between individual features. Although the p-values for several pairs were below 0.05, they remained above the Bonferroni-adjusted significance threshold of 0.0033 (0.05/15). Specifically, the following pairs showed p-values below 0.05: sound-filtering vs line-tracing ($p = 0.009$), sound-filtering vs node-connections ($p = 0.035$), sound-filtering vs route-phase-split ($p = 0.005$), line-tracing vs route-only rendering ($p = 0.020$), and route-only rendering vs route-phase-split ($p = 0.008$). Therefore, based on the Bonferroni correction (15 pairwise tests), no significant differences in usefulness ratings were found between the immersive UI features.

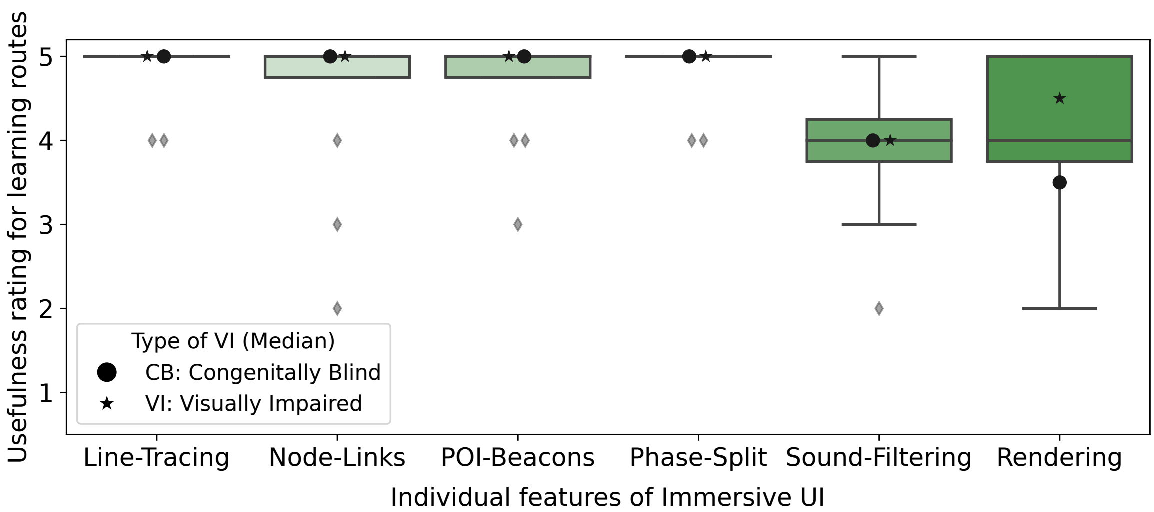

Figure 6.15.: Immersive UI individual features analysis - Usefulness rating. The boxplots illustrate the distribution of participants' usefulness ratings per Immersive UI feature.

Although no significant differences were observed between the individual features of the immersive UI, participant feedback highlighted both positive aspects and areas for improvement. The POI-Beacons feature received favourable comments, with participants noting "The POI ambient sounds were really great!" – (P2, VI) and "The points of interest background sounds are definitely the best!" – (P11, CB). In contrast, feedback on the sound-filtering and node-links features was less favourable, with participants stating "I did not need the sound filtering option." – (P3, CB), "It annoyed me. We can do better, like using speech would be easier for me." – (P8, VI) (node-links), and "There is potential for improvement. Use different instruments every two beeps to make it easier to count the station connections." – (P3, CB) (node-links).

An additional aspect of the immersive UI that was not previously discussed in the analysis but which received considerable attention was the pinpoint navigation feature designed to guide the user's finger to a specific location on the network map. Participants highlighted its significance and importance, noting that it played a crucial role in supporting navigation, "The audio navigation to the starting point is necessary for independent learning." – (P1, CB), "I do not get lost with the second UI (immersive) since we have the audio navigation." – (P9, VI). Participants also noted the absence of this feature in the tap-to-hear UI, highlighting its importance for efficient navigation, "We need navigation! Where can I find the last point when I do a left or right shift of the map?" – (P5, VI).

Immersive UI - Scalability Analysis

During the semi-structured interviews, participants were asked about potential scalability applications for the immersive UI. Several participants identified practical use cases, particularly for indoor floor plans and city map route navigation: "Mostly for city maps and route navigation." – (P2, VI), "In long-distance train networks and for learning walking routes on a city map." – (P3, CB), and "I can see it in indoor floor-plans or city maps where we use the sound of traffic lights and bus stops as POI beacons." – (P4, CB). In addition to these practical applications, some participants proposed more unconventional scalability ideas, including: "Follow the nerves and blood streams on a human body graphic." – (P9, VI) and "IT diagrams such as UML decision graphs." – (P10, CB).

6.3.3. Discussion

Investigating user interfaces for exploring travel routes on complex network maps has provided valuable insights, advancing the development of 2D refreshable tactile pin displays and improving accessibility to intricate 2D information. The discussion highlights the immersive UI's superior performance in task completion, efficiency, and user satisfaction while also addressing discrepancies in its perceived usefulness. Additionally, it explores the impact of perceived map complexity on user experience, offering a comprehensive understanding of how such advanced UIs can enhance accessibility for individuals with BVI.

Immersive UI: A Clear Distinction

The immersive map-route exploration UI demonstrated significantly higher effectiveness than the tap-to-hear map-route exploration UI for exploring complex travel routes on large network maps. While prior research on path-assist learning has primarily focused on effectiveness and user learning outcomes [281], the immersive solution also outperformed the tap-to-hear UI in terms of both efficiency and user satisfaction.

Participants correctly completed the majority of assigned tasks with the immersive UI (mean = 9.25 out of 10), a performance not observed with the tap-to-hear UI (mean = 3.92 out of 10), where less than half of the tasks were completed. The immersive UI enabled users to comprehend and learn realistic travel routes thoroughly, highlighting the essential role of advanced user interfaces in facilitating route learning for individuals with BVI on large, complex network maps. Furthermore, participants completed tasks approximately 1.33 times faster (986/742) with the immersive UI, and cognitive load, as measured by NASA-TLX, was significantly lower compared to the tap-to-hear UI: "It was very quick to learn with the immersive UI." – (P1, CB). The tap-to-hear UI received a mean SUS score of 55.63, below the average benchmark (68), whereas the immersive UI achieved a mean score of 82.08, indicating a high level of usability(>80), as supported by past research [23, 258]. The high satisfaction with the immersive UI was not only due to its usability but also its engaging nature. Participants found the immersive UI enjoyable, highlighting its potential to enhance both learning and motivation: "It is really fun with the immersive UI, and the fun really helps." – (P12, CB).

These findings are even more notable considering participants were introduced to the immersive UI for the first time with only a brief 10-15 minute training session. Furthermore, the immersive UI proved effective for both types of visually impaired users, with no significant differences in efficiency, effectiveness, or satisfaction between the groups. This demonstrates that such an interface can benefit a broad range of users, extending beyond fully blind or visually impaired individuals.

Discrepancies in the Immersive UI

The analysis of the immersive UI components revealed valuable insights and notable challenges. Although all participants preferred the immersive UI, which demonstrated superior efficiency and effectiveness for exploring travel routes, it was not perceived uniformly by all users and was not without limitations.

Results indicated no statistically significant differences in the perceived usefulness of the main features of the immersive UI. However, sound-filtering and rendering features were, on average, rated as less helpful than others. This discrepancy may be attributed to participants' varying levels of experience with assistive technologies and their adaptability to multimodal systems: "I did not need the sound-filtering option." – (P3, CB). Additionally, these features were not necessary for completing the study tasks, unlike the other functionalities (line-tracing, node-links, POI-beacons, and phase-split). Nevertheless, the sound-filtering and rendering functionalities received an average usefulness rating close to 4, thereby offering significant value to users who found them necessary for mitigating information overload.

While all features enabled participants to perform the route-learning tasks, several participants identified areas for improvement, particularly for the node-links feature: "It annoyed me. We can do better, like using speech would be easier for me." – (P8, VI), and "There is potential for improvement. Use different instruments every two beeps to make it easier to count the station connections." – (P3, CB). These suggestions reflect individual likings and prior experiences with assistive technologies, including familiarity with musical instruments or a preference for speech-based versus sonification-based user interfaces.

Discrepancies were also observed in participants' scalability suggestions. While some focused on similar applications such as indoor and city maps navigation —"Mostly for city maps and route navigation." – (P2, VI), "In long-distance train networks and for learning walking routes on a city map." – (P3, CB)—others proposed innovative applications beyond typical use cases. Examples included medical visualizations—"Follow the nerves and blood streams on a human body graphic." – (P9, VI)—and technical diagrams such as UML decision graphs—"IT diagrams such as UML decision graphs." – (P10, CB).

Overall, these findings underscore the inherent challenges in designing universally ideal user interfaces. Even within a focused group of individuals with BVI, significant differences and discrepancies in preferences, needs, and perceptions emerge. These variations highlight the difficulty of creating an interface that is entirely free of disadvantages or universally satisfying for all users, emphasizing the importance of adaptable and customizable designs to accommodate diverse user experiences.

Perceived Map Complexity

This study utilized highly complex network maps to evaluate the route exploration user interfaces under realistic conditions rather than simplified scenarios. Analysis revealed no statistically significant differences in effectiveness or efficiency between the Paris and Madrid maps. The counterbalanced design, which evenly varied the order of maps with user interfaces, further supports the conclusion that both maps had comparable difficulty levels. Additionally, user difficulty ratings aligned with these findings, showing no significant differences and confirming the maps' comparable complexity.

Nevertheless, a significant difference emerged when map difficulty ratings were analysed per UI. Participants rated the network maps explored with the tap-to-hear UI as more complex compared to those used with the immersive UI: "5 is not enough! I would give it a 10!" – (P8, VI) (when evaluating the map's difficulty on a scale of 1 to 5). This highlights the role of user interface design in reducing perceived difficulty and enhancing the clarity of complex information environments.

Interestingly, the average difficulty ratings for Paris (3.00) and Madrid (3.33) were lower than expected, as initial predictions anticipated ratings between 4 and 5. Despite the large scale and complexity of the maps and the participants' lack of prior experience with such extensive networks or the technology itself, many indicated that even more challenging maps could be explored. Similarly, the low difficulty rating for the tutorial map, Nuremberg (slightly above 1), reflects its relative simplicity in comparison. These findings highlight the high expectations participants hold for assistive technology, envisioning future advancements that would enable access to even more complex information comparable to that available to sighted users.

6.4. CONCLUSION AND FINDINGS

Learning and exploring realistic travel routes pose significant challenges for individuals with BVI. 2D refreshable tactile pin displays hold the potential to be an effective, efficient, and satisfactory solution, transforming these challenges into intuitive experiences.

Building on state-of-the-art approaches, the tap-to-hear exploration UI was developed and tested with nine BVI participants who used the Nuremberg metro network map to learn a simple route. While the UI showed promise, it still fell short of fully addressing the challenge, with participants expressing frustration and a need for more comprehensive information representation and faster solutions. Suggestions for improvement emphasised greater flexibility in the information provided and a more effective use of audio. When exploring potential applications for the UI, the focus remained on navigation and geographical contexts, overlooking potential uses in other areas.

Following a human-centred design approach and incorporating users' improvement suggestions led to the development of the immersive map-travel exploration UI. This interface enhanced the tap-to-hear solution by introducing dynamic components designed to optimise the use of audio-tactile information and mitigate information overload, including phase-split navigation, line tracing, POI audio-beacons, node connection feedback, and element filtering/muting. Both solutions were evaluated in a user study with 12 BVI participants, who explored complex routes on large metro network maps (Paris and Madrid) as part of a realistic scenario. Statistical analysis revealed that the immersive UI was significantly more efficient, effective, and satisfying for learning travel routes on network maps compared to the tap-to-hear UI. This is particularly noteworthy given that participants had only 10-15 minutes of training with each user interface. This suggests that with more time and training, users could have gained even more familiarity and proficiency with the method, enhancing their overall experience.

In contrast to the tap-to-hear user interface, participants found the immersive UI potentially helpful in contexts beyond navigation and geographical applications, including the exploration of medical visualisations and technical diagrams. While the immersive UI outperformed the tap-to-hear interface in all aspects, it was not universally perceived, with notable differences in preferences and needs among participants. Such variations underscore the challenge of designing a one-size-fits-all interface and highlight the need for adaptable and customizable solutions that accommodate diverse user experiences.

These findings offer valuable insights into the design of refreshable audio-tactile map exploration systems that address complex, realistic travel routes rather than simplified, theoretical ones. To deepen our understanding, we now turn to Research Question 3 and its sub-questions, focusing on key aspects of accessible travel route exploration on tactile maps for BVI users.

Answering Research Question 3

RQ3.1: To what extent can current state-of-the-art audio-tactile UIs help BVI individuals efficiently and effectively learn and explore travel routes in network maps?

Findings from the first usability study concluded that the current state-of-the-art audio-tactile UI, tap-to-hear map-route exploration, shows promise but does not fully address the challenge, even on a relatively small-scale network (see Section 6.2). It received a usability score of only 2.67 out of 5, indicating moderate user satisfaction but clear room for improvement. The second usability study reinforced these findings, with users correctly completing only 3.08 out of 10 learning/exploration tasks using the tap-to-hear UI (see Section 6.3). Participants expressed frustration and dissatisfaction, highlighting the limitations of the current SOTA solution for the task.

RQ3.2: What key design factors contribute to an effective dynamic audio-tactile user interface for assisting BVI individuals in learning complex map routes while optimising both efficiency and user satisfaction?

During the first usability study, participants highlighted the need for greater flexibility and improved audio use in the SOTA tap-to-hear exploration (see Section 6.2). The second study showed that the proposed Immersive UI outperformed the current SOTA tap-to-hear UI in terms of efficiency, effectiveness, and user satisfaction when assisting BVI individuals in learning and exploring complex travel routes in large network maps (see Section 6.3).

Both Line Tracing and Sonoice Navigation, previously used to address other research questions, were also effective in this key challenge, highlighting the scalability potential that such UIs hold. While zooming and panning features are helpful for exploring graphics on 2DRTP displays, our results showed that phase-split navigation from the Immersive UI was more effective in helping users explore each route phase. This key design feature incorporated Sonoice navigation to guide users' hands to the route start, addressing the focus issues seen with zooming and panning. Phase-split navigation received a high usefulness rating of 4.83 out of 5, highlighting its significance in improving both learning and efficiency. Line Tracing was identified as another key design factor, enabling users to follow the travel route while keeping other routes and background information visible. This feature also received a high rating of 4.83 out of 5. Even with the option to display only the route, participants preferred to show all lines for context and filter the relevant line using Line Tracing, further confirming its effectiveness.

While Sound Filtering did not receive the highest usefulness rating, it was particularly appreciated by beginner users who needed assistance handling the information. As such, we consider it an essential design feature to ensure a more universal interface.

Ambient POI beacons were also well-received by users, sparking enthusiasm and highlighting their potential as key design factors for gamifying the experience and providing additional information without overwhelming the user.

Part III.

INSIGHTS

7. CONCLUSIONS

This dissertation contributes to the research field by designing, implementing, and empirically validating dynamic audio-tactile user interface solutions tailored to real-world, complex information, reflecting the actual needs and tasks of blind and visually impaired (BVI) individuals. In all three graphics accessibility challenges, the designed user interfaces consistently achieve meaningful improvements over state-of-the-art approaches, demonstrating their usability, effectiveness, and potential for real-world impact. For pinpointing elements in tactile surfaces, combining sonification with voice offers an efficient, superior solution that adapts to natural diagonal hand movements and performs consistently well across complex tactile graphics. Key user interface features for exploring complex line charts effectively include using a musical environment to help users correlate lines simultaneously and responsive audio line tracing to help users learn each line's shape and boundaries. To learn complex travel routes in network maps, a customizable, immersive 2D tactile interface best enables users to follow routes phase by phase through line tracing, explore line nodes and beacons through structured audio-tactile feedback, and filter relevant data. This chapter summarises the main contributions and insights of this dissertation.

7.1. PINPOINT NAVIGATION

To support BVI users in navigating tactile graphics, we designed and evaluated four user interfaces: Voice (directional speech), Sonar (proximity-based beeps), Axis (trigger linear beep guidance), and Sonoice (a combination of sonification and voice). Our findings demonstrate that Sonoice navigation outperforms the others in efficiency, showing that combining voice and sonification offers a markedly superior solution. Although multimodal approaches remain uncommon in current assistive technologies and unfamiliar to many users, our results reveal that with as little as 15 minutes of training, users navigate tactile graphics significantly more efficiently using the Sonoice interface.

The tactile layout of a graphic can make navigation more challenging and unintentionally misguide users, especially when uneven tactile elements lead to diagonal drifting instead of following straight paths. Interfaces such as Axis, which depend on maintaining straight hand movements, prove difficult for users, particularly on larger tactile graphics, causing hand misalignment and frustration. Effective navigation systems must adapt to natural, often diagonal, hand movements rather than enforcing rigid paths. This holds true for both the Sonar and Voice interfaces, but especially for the Sonoice navigation interface, which performs consistently well on both simple and complex tactile graphics.

7.2. LINE CHART EXPLORATION

To help BVI users learn and explore complex line charts, we designed and evaluated three user interfaces: Tap-to-hear (standard element-by-element exploration), Trigger (trigger-intersection multi-line view with line-trace guidance), and Melodic (melody environment with line-trace guidance). Our findings demonstrate that a Melodic user interface is the superior solution, outperforming the other solutions in effectiveness and user satisfaction, without prolonging interaction times. Such a level of performance led to users confidently exploring complex line charts with up to nine lines and numerous intersections and overlaps, something not achieved in related work.

We conclude that the main factor for designing good user interfaces for exploring line charts is the ability to support individual audio line tracing, allowing users to understand each line's shape, peaks, troughs, and boundaries within the chart. However, line tracing alone proved insufficient, as shown by the Trigger solution, highlighting the need for a multi-line representation. Our innovative way to help users compare and correlate across lines was the use of a melodic environment with distinct instruments, creating a harmonically pleasant and engaging interaction that supports both advanced and novice users in learning complex line charts.

7.3. TRAVEL ROUTE LEARNING

To assist BVI individuals in learning and exploring travel routes on tactile maps, we designed and evaluated two user interfaces on 2D refreshable tactile pin displays: Tap-to-hear (a standard exploration method) and Immersive (a more flexible, audio-augmented approach). Our findings show that the Immersive user interface offers a superior solution for learning and navigating complex travel routes on large-scale maps, even allowing users to efficiently learn real routes in the large Paris and Madrid network maps.

Although standard tap-to-hear is widely used for learning tactile graphics, dynamic zooming and panning capabilities prove insufficient for navigating complex, real-world route networks. We recommend enhancing this interface by splitting routes into smaller segments and employing Sonoice navigation to guide users to the start of each segment, helping them maintain focus. For following the route itself, line-tracing guidance, previously effective in learning line charts, has also proven effective in this context. Additionally, replacing or complementing text-based information with ambient sounds for points of interest helps reduce information overload, a feature that users enthusiastically received. It is crucial that these features are customizable and can be toggled on or off to accommodate both advanced users who may not require all aids constantly and novices who benefit from full support.

7.4. OUTLOOK

As is common in assistive technology development, solutions are often broadly applicable across different challenge contexts and adaptable to various devices. In this dissertation, we aimed to design user interfaces with such scalability in mind, targeting both tactile graphic readers and 2D refreshable tactile pin displays. For example, the user interfaces developed in Chapters 4 and 5 were initially implemented on the Tactonom Reader, a tactile graphic reader, but can be directly transferred to 2D refreshable tactile displays by replacing the tactile paper with dynamic pin-based output. In addition to device expandability, each user interface developed in this dissertation is not just valuable for its original challenge but also shows promise for supporting BVI individuals in other graphic accessibility contexts. A concrete example of the developed solutions' high scalability capability is our adaptation of the Sonoice algorithm from pinpoint navigation, along with line tracing from line chart exploration, in the design of the Immersive UI for learning travel routes. During usability studies, we explored participants' views on potential applications of these UIs in other contexts and for addressing different graphic accessibility challenges. These findings highlight promising future directions, such as applying audio-tactile user interfaces to support interaction with email clients, 2D calendars, file explorers, spreadsheets, word processors, and other task-oriented environments requiring access to structured graphical information.

While this research primarily enhances accessibility for BVI individuals, there is also significant potential in exploring the impact of dynamic audio-tactile UIs for sighted users. Future work could examine how interfaces combining visual with dynamic audio-tactile elements could serve both groups, allowing them to interact with the same system in complementary ways. This could lead to dual-purpose interfaces that enrich the experience for sighted users by adding interactivity through audio and tactile feedback, aligning with the broader goal of creating a more connected, inclusive world where technology offers universal benefits, transcending traditional accessibility boundaries.

The evolution of tactile graphic readers and 2D refreshable displays is only in its early phases. This research demonstrates the immense potential of these devices and highlights the critical role of user interface design in unlocking that potential. Beyond addressing real-world challenges and empowering users to access previously inaccessible complex information, it opens new possibilities for reshaping audio-tactile interaction and how such information is perceived. The future of this technology rests in the hands of researchers, developers, and, most importantly, the users, whose insights, needs, and lived experiences must guide its evolution. Only through this shared effort can we shape tactile graphics and 2D refreshable displays into truly inclusive tools that are deeply integrated into everyday life, embraced across diverse domains, and capable of making meaningful access a reality for all.

BIBLIOGRAPHY

[1] America Printing House (APH). *The Tactile Graphics Image Library: Helping Students Succeed.* 2022. URL: https://imagelibrary.aph.org/aphb/.

[2] European Blind Union (EBU). *About blindness and partial sight.* 2020. DOI: 1. URL: http://www.euroblind.org/about-blindness-and-partial-sight/facts-and-figures/.

[3] World Health Organisation (WHO). *Blindness and vision impairment.* 2021. DOI: 2. URL: https://www.who.int/news-room/fact-sheets/detail/blindness-and-visual-impairment.

[4] 4Blind. *Braille PAD - tactile tablet.* 2023. URL: https://4blind.com/solutions-en/braille_pad_en.

[5] Nazatul Naquiah Abd Hamid and Alistair D.N. Edwards. "Facilitating Route Learning Using Interactive Audio-Tactile Maps for Blind and Visually Impaired People". In: *CHI '13 Extended Abstracts on Human Factors in Computing Systems.* CHI EA '13. Paris, France: Association for Computing Machinery, 2013, pp. 37–42. ISBN: 9781450319522. DOI: 10.1145/2468356.2468364. URL: https://doi.org/10.1145/2468356.2468364.

[6] Metec AG. *BrailleDis 6240 (Also known as HyperBraille F).* 2016. URL: https://metec-ag.de/downloads/hyperbraille-f.pdf.

[7] Metec AG. *HyperBraille Project.* 2010. URL: http://hyperbraille.de/.

[8] Metec AG. *Hyperflat - Graphic and Braille Tablet Display for Visually Impaired Individuals.* 2016. URL: https://metec-ag.de/downloads/hyperflat-flyer-komplett.pdf.

[9] Metec AG. *Tactile2D - The "Laptop for the Blind".* 2020. URL: https://metec-ag.de/downloads/tactile2d-flyer.pdf.

[10] Teemu Ahmaniemi, Vuokko Lantz, and Juha Marila. "Dynamic audiotactile feedback in gesture interaction". In: *Proceedings of the 10th International Conference on Human Computer Interaction with Mobile Devices and Services.* MobileHCI '08. Amsterdam, The Netherlands: Association for Computing Machinery, 2008, pp. 339–342. ISBN: 9781595939524. DOI: 10.1145/1409240.1409283. URL: https://doi.org/10.1145/1409240.1409283.

[11] Dragan Ahmetovic, Federico Avanzini, Adriano Baratè, Cristian Bernareggi, Marco Ciardullo, Gabriele Galimberti, Luca A. Ludovico, Sergio Mascetti, and Giorgio Presti. "Sonification of navigation instructions for people with visual impairment". In: *International Journal of Human-Computer Studies* 177 (2023), p. 103057. ISSN: 1071-5819. DOI: https://doi.org/10.1016/j.ijhcs.2023.103057. URL: https://www.sciencedirect.com/science/article/pii/S1071581923000666.

[12] Dragan Ahmetovic, Federico Avanzini, Adriano Baratè, Cristian Bernareggi, Gabriele Galimberti, Luca A. Ludovico, Sergio Mascetti, and Giorgio Presti. "Sonification of Pathways for People with Visual Impairments". In: *Proceedings of the 20th International ACM SIGACCESS Conference on Computers and Accessibility*. ASSETS '18. Galway, Ireland: Association for Computing Machinery, 2018, pp. 379–381. ISBN: 9781450356503. DOI: 10.1145/3234695.3241005. URL: https://doi.org/10.1145/3234695.3241005.

[13] Dragan Ahmetovic, Federico Avanzini, Adriano Baratè, Cristian Bernareggi, Gabriele Galimberti, Luca A. Ludovico, Sergio Mascetti, and Giorgio Presti. "Sonification of Rotation Instructions to Support Navigation of People with Visual Impairment". In: *2019 IEEE International Conference on Pervasive Computing and Communications (PerCom*. Kyoto, Japan: IEEE Computer Science, 2019, pp. 1–10. DOI: 10.1109/PERCOM.2019.8767407. URL: https://doi.org/10.1109/PERCOM.2019.8767407.

[14] Dragan Ahmetovic, Cristian Bernareggi, João Guerreiro, Sergio Mascetti, and Anna Capietto. "AudioFunctions.web: Multimodal Exploration of Mathematical Function Graphs". In: *Proceedings of the 16th International Web for All Conference*. W4A '19. San Francisco, CA, USA: Association for Computing Machinery, 2019. ISBN: 9781450367165. DOI: 10.1145/3315002.3317560. URL: https://doi.org/10.1145/3315002.3317560.

[15] Dragan Ahmetovic, Cristian Bernareggi, Sergio Mascetti, and Federico Pini. "SoundLines: Exploration of Line Segments through Sonification and Multi-Touch Interaction". In: *Proceedings of the 22nd International ACM SIGACCESS Conference on Computers and Accessibility*. ASSETS '20. Virtual Event, Greece: Association for Computing Machinery, 2020. ISBN: 9781450371032. DOI: 10.1145/3373625.3418041. URL: https://doi.org/10.1145/3373625.3418041.

[16] Md Zubair Ibne Alam, Shehnaz Islam, and Enamul Hoque. "SeeChart: Enabling Accessible Visualizations Through Interactive Natural Language Interface For People with Visual Impairments". In: *Proceedings of the 28th International Conference on Intelligent User Interfaces*. IUI '23. Sydney, NSW, Australia: Association for Computing Machinery, 2023, pp. 46–64. DOI: 10.1145/3581641.3584099. URL: https://doi.org/10.1145/3581641.3584099.

[17] Peter Albert. "Math class: An application for dynamic tactile graphics". In: *Computers Helping People with Special Needs: 10th International Conference, ICCHP 2006, Linz, Austria, July 11-13, 2006. Proceedings 10*. Springer. 2006, pp. 1118–1121. URL: https://doi.org/10.1007/11788713_162.

[18] Frances K. Aldrich and Alan J. Parkin. "Tangible Line Graphs: An Experimental Investigation of Three Formats Using Capsule Paper". In: *Human Factors* 29.3 (1987), pp. 301–309. DOI: 10.1177/001872088702900304. eprint: https://doi.org/10.1177/001872088702900304. URL: https://doi.org/10.1177/001872088702900304.

[19] Frances K. Aldrich and Linda Sheppard. "Tactile graphics in school education: perspectives from pupils". In: *British Journal of Visual Impairment* 19.2 (2001), pp. 69–73. DOI: 10.1177/026461960101900204. eprint: https://doi.org/10.1177/026461960101900204. URL: https://doi.org/10.1177/026461960101900204.

[20] Julia Anken, Danilo Rosenthal, Karin Müller, Gerhard Jaworek, and Rainer Stiefelhagen. "Split it Up: Allocentric Descriptions of Indoor Maps for People with Visual Impairments". In: *Computers Helping People with Special Needs*. Ed. by Klaus Miesenberger, Georgios Kouroupetroglou, Katerina Mavrou, Roberto Manduchi, Mario Covarrubias Rodriguez, and Petr Penáz. Cham: Springer International Publishing, 2022, pp. 102–109. ISBN: 978-3-031-08648-9. URL: https://doi.org/10.1007/978-3-031-08648-9_13.

[21] H. K. Ault, J. W. Deloge, R. W. Lapp, M. J. Morgan, and J. R. Barnett. "Evaluation of Long Descriptions of Statistical Graphics for Blind and Low Vision Web Users". In: *Computers Helping People with Special Needs*. Ed. by Klaus Miesenberger, Joachim Klaus, and Wolfgang Zagler. Berlin, Heidelberg: Springer Berlin Heidelberg, 2002, pp. 517–526. ISBN: 978-3-540-45491-5.

[22] Catherine M. Baker, Lauren R. Milne, Jeffrey Scofield, Cynthia L. Bennett, and Richard E. Ladner. "Tactile Graphics with a Voice: Using QR Codes to Access Text in Tactile Graphics". In: *Proceedings of the 16th International ACM SIGACCESS Conference on Computers & Accessibility*. ASSETS '14. Rochester, New York, USA: Association for Computing Machinery, 2014, pp. 75–82. ISBN: 9781450327206. DOI: 10.1145/2661334.2661366. URL: https://doi.org/10.1145/2661334.2661366.

[23] Aaron Bangor, Philip Kortum, and James Miller. "Determining What Individual SUS Scores Mean: Adding an Adjective Rating Scale". In: *J. Usability Studies* 4.3 (May 2009), pp. 114–123.

[24] Aaron Bangor, Philip T. Kortum, and James T. Miller and. "An Empirical Evaluation of the System Usability Scale". In: *International Journal of Human–Computer Interaction* 24.6 (2008), pp. 574–594. DOI: 10.1080/10447310802205776. eprint: https://doi.org/10.1080/10447310802205776. URL: https://doi.org/10.1080/10447310802205776.

[25] Woodrow Barfield and III Furness Thomas A. *Virtual Environments and Advanced Interface Design*. Oxford University Press, July 1995. ISBN: 9780195075557. DOI: 10.1093/oso/9780195075557.001.0001. URL: https://doi.org/10.1093/oso/9780195075557.001.0001.

[26] Yacine Bellik and Dominique Burger. "Multimodal interfaces: new solutions to the problem of computer accessibilty for the blind". In: *Conference Companion on Human Factors in Computing Systems* (1994). URL: https://api.semanticscholar.org/CorpusID:16342759.

[27] M. Benali-Khoudja, M. Hafez, J.-M. Alexandre, and A. Kheddar. "Electromagnetically driven high-density tactile interface based on a multi-layer approach". In: *MHS2003. Proceedings of 2003 International Symposium on Micromechatronics and Human Science (IEEE Cat. No.03TH8717).* 2003, pp. 147–152. DOI: 10.1109/MHS.2003.1249924.

[28] Cristian Bernareggi. *TOWARDS AN ACCESSIBLE SCIENCE: FACILITATING ACCESS TO SCIENTIFIC DIGITAL RESOURCES FOR VISUALLY IMPAIRED STUDENTS.* Deliverable D2.1. Dissemination level: Restricted. Università degli Studi di Milano, June 2007.

[29] N. Besse, S. Rosset, J. J. Zárate, C. Lorini, G. Zini, F. Bertora, D. Torazza, L. Brayda, and H. Shea. *32x24 SMP prototype.* Accessed 2013. 2017. URL: https://youtu.be/AOnj-4xYA6s.

[30] Nadine Besse. *Large array of shape memory polymer actuators for haptics and microfluidics.* Tech. rep. EPFL, 2018. URL: https://api.semanticscholar.org/CorpusID:115354053.

[31] Nadine Besse, Samuel Rosset, Juan Jose Zarate, and Herbert Shea. "Flexible Active Skin: Large Reconfigurable Arrays of Individually Addressed Shape Memory Polymer Actuators". In: *Advanced Materials Technologies* 2.10 (2017), p. 1700102. DOI: https://doi.org/10.1002/admt.201700102. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/admt.201700102. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/admt.201700102.

[32] Nadine Besse, Samuel Rosset, Juan José Zárate, Elisabetta Ferrari, Luca Brayda, and Herbert Shea. "Understanding Graphics on a Scalable Latching Assistive Haptic Display Using a Shape Memory Polymer Membrane". In: *IEEE Transactions on Haptics* 11.1 (2018), pp. 30–38. DOI: 10.1109/TOH.2017.2767049. URL: https://doi.org/10.1109/TOH.2017.2767049.

[33] Nadine Besse, Juan J. Zárate, Samuel Rosset, and Herbert R. Shea. "Flexible haptic display with 768 independently controllable shape memory polymers taxels". In: *2017 19th International Conference on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS).* 2017, pp. 323–326. DOI: 10.1109/TRANSDUCERS.2017.7994054. URL: https://doi.org/10.1109/TRANSDUCERS.2017.7994054.

[34] Tigmanshu Bhatnagar, Nicolai Marquardt, Mark Miodownik, and Catherine Holloway. "Transforming a Monolithic Sheet of Nitinol into a Passive Reconfigurable Tactile Pixel Array Display at Braille Resolution". In: *2021 IEEE World Haptics Conference (WHC).* 2021, pp. 409–414. DOI: 10.1109/WHC49131.2021.9517239. URL: https://doi.org/10.1109/WHC49131.2021.9517239.

[35] Tigmanshu Bhatnagar, Vikas Upadhyay, Anchal Sharma, P V Madhusudhan Rao, Mark Miodownik, Nicolai Marquardt, and Catherine Holloway. "Pixelated Interactions: Exploring Pixel Art for Graphical Primitives on a Pin Array Tactile Display". In: *Proceedings of the 2023 ACM Designing Interactive Systems Conference*. DIS '23. Pittsburgh, PA, USA: Association for Computing Machinery, 2023, pp. 1194–1208. ISBN: 9781450398930. DOI: 10.1145/3563657.3596044. URL: https://doi.org/10.1145/3563657.3596044.

[36] Tigmanshu Bhatnagar, Vikas Upadhyay, Anchal Sharma, PV Madhusudhan Rao, Mark Miodownik, Nicolai Marquardt, and Catherine Holloway. "Drawing Erasable Tactile Diagrams on Tacilia". In: *Proceedings of the 2021 IEEE World Haptics Conference (WHC)*. IEEE. Montreal, Canada, July 2021. URL: https://discovery.ucl.ac.uk/id/eprint/10131452/1/0272.pdf.

[37] American Foundation for the Blind. *Reviewing Charts and Graphs with SAS Accessibility*. AccessWorld, July 2018. Accessed: 2025-02-15. 2018. URL: https://www.afb.org/.

[38] BlindSquare. *BlindSquare iOS Application*. BlindSquare. 2025. URL: https://www.blindsquare.com/.

[39] Susanne Bødker. "Through the Interface - a Human Activity Approach to User Interface Design". In: *DAIMI Report Series* 16.224 (Apr. 1987). DOI: 10.7146/dpb.v16i224.7586. URL: https://tidsskrift.dk/daimipb/article/view/7586.

[40] Susanne Bødker, Christian Dindler, Ole S. Iversen, and Rachel C. Smith. "What Is Participatory Design?" In: *Participatory Design*. Cham: Springer International Publishing, 2022, pp. 5–13. ISBN: 978-3-031-02235-7. DOI: 10.1007/978-3-031-02235-7_2. URL: https://doi.org/10.1007/978-3-031-02235-7_2.

[41] Karin Böhm. *Gesundheit. Auszug aus dem Datenreport 2021*. Tech. rep. Statistisches Bundesamt (Destatis), 2021.

[42] Denise Bornschein. "Redesigning Input Controls of a Touch-Sensitive Pin-Matrix Device". In: *TacTT@ITS*. CEUR Workshop Proceedings 1324 (Nov. 2014). Ed. by Limin Zeng and Gerhard Weber, pp. 19–24. URL: http://ceur-ws.org/Vol-1324/Preface.pdf.

[43] Denise Bornschein, Jens Bornschein, Wiebke Köhlmann, and Gerhard Weber. "Touching graphical applications: bimanual tactile interaction on the HyperBraille pin-matrix display". In: *Universal Access in the Information Society* 17 (June 2018). DOI: 10.1007/s10209-017-0538-8. URL: https://ieeexplore.ieee.org/document/9765568.

[44] J. Bornschein, G. Weber, and T. Götzelmann. *Multimodales kollaboratives Zeichensystem für blinde Benutzer*. Dresden, Germany: Technische Universität Dresden, 2020. URL: https://books.google.de/books?id=NVMizgEACAAJ.

[45] Jens Bornschein. "A Multimodal and Collaborative Drawing Workstation for Blind Users". PhD thesis. Technische Universität Dresden, 2020. URL: https://tud.qucosa.de/api/qucosa%3A71516/attachment/ATT-0/?L=1.

[46] Jens Bornschein. "BrailleIO - a Tactile Display Abstraction Framework". In: *TacTT@ITS* 1324 (Nov. 2014), pp. 36–41. URL: https://ceur-ws.org/Vol-1324/paper_4.pdf.

[47] Jens Bornschein. *BrailleIO: A 2D tactile pin-matrix device abstraction framework.* 2014. URL: https://github.com/TUD-INF-IAI-MCI/BrailleIO.

[48] Jens Bornschein, Denise Bornschein, and Gerhard Weber. "Blind Pictionary: Drawing Application for Blind Users". In: *CHI 2018*. CHI EA '18. Montreal QC, Canada: Association for Computing Machinery, 2018, pp. 1–4. ISBN: 9781450356213. DOI: 10.1145/3170427.3186487. URL: https://doi.org/10.1145/3170427.3186487.

[49] Jens Bornschein, Denise Bornschein, and Gerhard Weber. "Comparing Computer-Based Drawing Methods for Blind People with Real-Time Tactile Feedback". In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI '18. Montreal QC, Canada: Association for Computing Machinery, 2018, pp. 1–13. ISBN: 9781450356206. DOI: 10.1145/3173574.3173689. URL: https://doi.org/10.1145/3173574.3173689.

[50] Jens Bornschein and Denise Prescher. "Collaborative Tactile Graphic Workstation for Touch-Sensitive Pin-Matrix Devices". In: *TacTT@ITS*. 2014. URL: https://ceur-ws.org/Vol-1324/paper_5.pdf.

[51] Jens Bornschein, Denise Prescher, and Gerhard Weber. "Collaborative Creation of Digital Tactile Graphics". In: *Proceedings of the 17th International ACM SIGACCESS Conference on Computers & Accessibility*. ASSETS '15. Lisbon, Portugal: Association for Computing Machinery, 2015, pp. 117–126. ISBN: 9781450334006. DOI: 10.1145/2700648.2809869. URL: https://doi.org/10.1145/2700648.2809869.

[52] Jens Bornschein, Denise Prescher, and Gerhard Weber. "SVGPlott – Generating Adaptive and Accessible Audio-Tactile Function Graphs". In: *Computers Helping People with Special Needs*. Ed. by Klaus Miesenberger, Deborah Fels, Dominique Archambault, Petr Peňáz, and Wolfgang Zagler. Cham: Springer International Publishing, 2014, pp. 588–595. ISBN: 978-3-319-08596-8.

[53] Braille Authority of North America. *Unified English Braille Formats and Guidelines.* 2016. URL: http://brailleauthority.org/formats/formats2016.html.

[54] Luca Brayda, Fabrizio Leo, Caterina Baccelliere, Elisabetta Ferrari, and Claudia Vigini. "Updated Tactile Feedback with a Pin Array Matrix Helps Blind People to Reduce Self-Location Errors". In: *Micromachines* 9.7 (2018). ISSN: 2072-666X. DOI: 10.3390/mi9070351. URL: https://www.mdpi.com/2072-666X/9/7/351.

[55] Bristol-Braille. *Canute UI.* User interface for the Canute electronic Braille reader. 2023. URL: https://github.com/Bristol-Braille/canute-ui.

[56] Anke Brock and Christophe Jouffrais. "Interactive Audio-Tactile Maps for Visually Impaired People". In: *SIGACCESS Access. Comput.* 113.113 (Nov. 2015), pp. 3–12. ISSN: 1558-2337. DOI: 10.1145/2850440.2850441. URL: https://doi.org/10.1145/2850440.2850441.

[57] Anke Brock, Bernard Oriola, Philippe Truillet, Christophe Jouffrais, and Delphine Picard. "Map design for visually impaired people: past, present, and future research". In: *MEI - Médiation et information*. Handicap et communication (2013), pp. 117–129. URL: https://hal.science/hal-01099497.

[58] Anke Brock, Philippe Truillet, Bernard Oriola, and Christophe Jouffrais. "Usage of multimodal maps for blind people: Why and how". In: Nov. 2010, pp. 247–248. DOI: 10.1145/1936652.1936699.

[59] Anke M. Brock, Philippe Truillet, Bernard Oriola, Delphine Picard, and Christophe Jouffrais. "Interactivity Improves Usability of Geographic Maps for Visually Impaired People". In: *Human–Computer Interaction* 30.2 (2015), pp. 156–194. DOI: 10.1080/07370024.2014.924412. eprint: https://doi.org/10.1080/07370024.2014.924412. URL: https://doi.org/10.1080/07370024.2014.924412.

[60] John Brooke. "SUS: a retrospective". In: *Journal of usability studies* 8.2 (2013), pp. 29–40.

[61] Michal Bujacz and Paweł Strumiłło. "Sonification: Review of Auditory Display Solutions in Electronic Travel Aids for the Blind". In: *Archives of Acoustics* 41 (2016), pp. 401–414. DOI: 10.1515/aoa-2016-0040. URL: https://api.semanticscholar.org/CorpusID:54979200.

[62] Matthew J Burton, Jacqueline Ramke, Ana Patricia Marques, Rupert R A Bourne, Nathan Congdon, Iain Jones, Brandon A M Ah Tong, Simon Arunga, Damodar Bachani, Covadonga Bascaran, Andrew Bastawrous, Karl Blanchet, Tasanee Braithwaite, John C Buchan, John Cairns, Anasaini Cama, Margarida Chagunda, Chimgee Chuluunkhuu, Andrew Cooper, Jessica Crofts-Lawrence, William H Dean, Alastair K Denniston, Joshua R Ehrlich, Paul M Emerson, Jennifer R Evans, Kevin D Frick, David S Friedman, João M Furtado, Michael M Gichangi, Stephen Gichuhi, Suzanne S Gilbert, Reeta Gurung, Esmael Habtamu, Peter Holland, Jost B Jonas, Pearse A Keane, Lisa Keay, Rohit C Khanna, Peng Tee Khaw, Hannah Kuper, Fatima Kyari, Van C Lansingh, Islay Mactaggart, Milka M Mafwiri, Wanjiku Mathenge, Ian McCormick, Priya Morjaria, Lizette Mowatt, Debbie Muirhead, Gudlavalleti V S Murthy, Nyawira Mwangi, Daksha B Patel, Tunde Peto, Babar M Qureshi, Solange R Salomão, Virginia Sarah, Bernadetha R Shilio, Anthony W Solomon, Bonnielin K Swenor, Hugh R Taylor, Ningli Wang, Aubrey Webson, Sheila K West, Tien Yin Wong, Richard Wormald, Sumrana Yasmin, Mayinuer Yusufu, Juan Carlos Silva, Serge Resnikoff, Thulasiraj Ravilla, Clare E Gilbert, Allen Foster, and Hannah B Faal. "The Lancet Global Health Commission on Global Eye Health: vision beyond 2020". In: *The Lancet Global Health* 9.4 (2021), e489–e551. DOI: 10.1016/S2214-109X(20)30488-5. URL: https://doi.org/10.1016/S2214-109X(20)30488-5.

[63] G. Byrd. "Tactile Digital Braille Display". In: *Computer* 49.11 (Nov. 2016), pp. 88–90. ISSN: 1558-0814. DOI: 10.1109/MC.2016.327. URL: https://doi.ieeecomputersociety.org/10.1109/MC.2016.327.

[64] Stanley J Cantrell, Bruce N Walker, and Øystein Moseng. "Highcharts Sonification Studio: An Online, Open-Source, Extensible, and Accessible Data Sonification Tool". In: *Proceedings of the 26th International Conference on Auditory Display (ICAD 2021). International Community for Auditory Display, Virtual Conference.* June 2021, pp. 210–216. DOI: 10.21785/icad2021.005.

[65] Jim Carter and David Fourney. "Research based tactile and haptic interaction guidelines". In: *Guidelines on Tactile and Haptic Interaction (GOTHI 2005)* (2005), pp. 84–92. URL: https://userlab.usask.ca/GOTHI/research.pdf.

[66] Elyse D. Z. Chase, Alexa Fay Siu, Abena Boadi-Agyemang, Gene S-H Kim, Eric J Gonzalez, and Sean Follmer. "PantoGuide: A Haptic and Audio Guidance System To Support Tactile Graphics Exploration". In: *The 22nd International ACM SIGACCESS Conference on Computers and Accessibility.* ASSETS '20. Virtual Event, Greece: Association for Computing Machinery, 2020. ISBN: 9781450371032. DOI: 10.1145/3373625.3418023. URL: https://doi.org/10.1145/3373625.3418023.

[67] Irene Grasso Chiara Meneghetti Erika Borella and Rossana De Beni. "Learning a route using a map and/or description in young and older adults". In: *Journal of Cognitive Psychology* 24.2 (2012), pp. 165–178. DOI: 10.1080/20445911.2011.603694. eprint: https://doi.org/10.1080/20445911.2011.603694. URL: https://doi.org/10.1080/20445911.2011.603694.

[68] Vasilios G Chouvardas, Amalia N Miliou, and Miltiadis K Hatalis. "Tactile displays: Overview and recent advances". In: *Displays* 29.3 (2008), pp. 185–194. URL: https://doi.org/10.1016/j.displa.2007.07.003.

[69] Vasilios G. Chouvardas, Amalia N. Miliou, and Miltiadis K. Hatalis. "Tactile display applications: a state of the art survey". In: *Proceedings of the 2nd Balkan Conference in Informatics.* Jan. 2005, pp. 290–303. URL: https://www.semanticscholar.org/paper/Tactile-display-applications%3A-a-state-of-the-art-Chouvardas-Miliou/8e62377e929b960b11febc943c18775199e54da8.

[70] Uniplan Co. *OUV3000.* 2006. URL: http://www.uniplan.gr.jp/OUV3000/index2.htm.

[71] Devin Coldewey. "Dot Pad Tactile Display Makes Images Touchable for Visually Impaired Users". In: *TechCrunch* (Mar. 2022). URL: https://techcrunch.com/2022/03/10/dot-pad-tactile-display-makes-images-touchable-for-visually-impaired-users/.

[72] Angela Constantinescu, Karin Müller, Monica Haurilet, Vanessa Petrausch, and Rainer Stiefelhagen. "Bring the Environment to Life: A Sonification Module for People with Visual Impairments to Improve Situation Awareness". In: *Proceedings of the 2020 International Conference on Multimodal Interaction.* ICMI '20. Virtual Event, Netherlands: Association for Computing Machinery, 2020, pp. 50–59. ISBN: 9781450375818. DOI: 10.1145/3382507.3418874. URL: https://doi.org/10.1145/3382507.3418874.

[73] Angela Constantinescu, Eva-Maria Neumann, Karin Müller, Gerhard Jaworek, and Rainer Stiefelhagen. "Listening First: Egocentric Textual Descriptions of Indoor Spaces for People with Blindness". In: *Computers Helping People with Special Needs*. Ed. by Klaus Miesenberger, Georgios Kouroupetroglou, Katerina Mavrou, Roberto Manduchi, Mario Covarrubias Rodriguez, and Petr Penáz. Cham: Springer International Publishing, 2022, pp. 241–249. ISBN: 978-3-031-08648-9. URL: `https://doi.org/10.1007/978-3-031-08648-9_28`.

[74] KGS Coporation. *Wellfare Braille equipments*. Accessed: 2023. URL: `https://www.kgs-jpn.co.jp/`.

[75] CORDIS/Europa.eu. *BLINDPAD: Personal Assistive Device for BLIND and visually impaired people*. Start date: 1 January 2014, End date: 31 May 2017. 2017. URL: `https://cordis.europa.eu/project/id/611621`.

[76] Tactisplay Corp. *TACTIS 100*. 2015. URL: `http://www.tactisplay.com/tactis-100-2/`.

[77] Tactisplay Corp. *TACTIS Table*. 2015. URL: `http://www.tactisplay.com/tactis-table-2/`.

[78] Tactisplay Corp. *TACTIS Walk*. 2015. URL: `http://www.tactisplay.com/tactis-walk-2/`.

[79] KGS Corporation. *Dot View DV-1*. 2002. URL: `https://www.kgs-jpn.co.jp/wp/wp-content/uploads/2022/05/DV1_manual_V10Rev1.pdf`.

[80] KGS Corporation. *Dot View DV-2*. 2003. URL: `https://www.kgs-jpn.co.jp/wp/wp-content/uploads/2022/05/DV-2_V10_manual_RevE.pdf`.

[81] James M Coughlan, Brandon Biggs, and Huiying Shen. "Point and Listen: Bringing a 3D Map to Life with Audio-Based AR". In: *Frameless* 4.1 (2022), p. 9. URL: `https://pubmed.ncbi.nlm.nih.gov/35620199/`.

[82] James M. Coughlan, Brandon Biggs, Marc-Aurèle Rivière, and Huiying Shen. "An Audio-Based 3D Spatial Guidance AR System for Blind Users". In: *Computers Helping People with Special Needs*. Ed. by Klaus Miesenberger, Roberto Manduchi, Mario Covarrubias Rodriguez, and Petr Peňáz. Cham: Springer International Publishing, 2020, pp. 475–484. ISBN: 978-3-030-58796-3. URL: `https://doi.org/10.1007/978-3-030-58796-3_55`.

[83] James M. Coughlan, Brandon Biggs, and Huiying Shen. "Non-visual Access to an Interactive 3D Map". In: *Computers Helping People with Special Needs*. Ed. by Klaus Miesenberger, Georgios Kouroupetroglou, Katerina Mavrou, Roberto Manduchi, Mario Covarrubias Rodriguez, and Petr Penáz. Cham: Springer International Publishing, 2022, pp. 253–260. ISBN: 978-3-031-08648-9. URL: `https://doi.org/10.1007/978-3-031-08648-9_29`.

[84] Creative Technology Limited. *OpenAL (Cross Platform 3D Audio)*. Creative Technology Limited. 2024. URL: `https://www.openal.org/`.

[85] Damien Di Fede. *Minim opensource audio processing library*. Compartmental. Apr. 2010. URL: `http://code.compartmental.net/tools/minim/`.

[86] Seniz Demir, Sandra Carberry, and Kathleen F. McCoy. “Generating textual summaries of bar charts”. In: *Proceedings of the Fifth International Natural Language Generation Conference*. INLG ’08. Salt Fork, Ohio: Association for Computational Linguistics, 2008, pp. 7–15.

[87] Tilman Dingler, Jeffrey Lindsay, and Bruce Walker. “Learnability of sound cues for environmental features: Auditory icons, earcons, spearcons, and speech”. In: *Proceedings of the 14th International Conference on Auditory Display, Paris, France* 2008 (2008). Ed. by International Community for Auditory Display. URL: https://api.semanticscholar.org/CorpusID:16755618.

[88] Judy Dixon. *Braille and Tactile Graphics at CSUN 2022*. AFB (American Foundation for the Blind). 2022. URL: https://afb.org/aw/23/4/17917.

[89] Julie Ducasse, Marc Macé, Bernard Oriola, and Christophe Jouffrais. “BotMap: Non-Visual Panning and Zooming with an Actuated Tabletop Tangible Interface”. In: *ACM Trans. Comput.-Hum. Interact.* 25.4 (Sept. 2018). ISSN: 1073-0516. DOI: 10.1145/3204460. URL: https://doi.org/10.1145/3204460.

[90] Julie Ducasse, Marc J-M Macé, Marcos Serrano, and Christophe Jouffrais. “Tangible Reels: Construction and Exploration of Tangible Maps by Visually Impaired Users”. In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. CHI ’16. San Jose, California, USA: Association for Computing Machinery, 2016, pp. 2186–2197. ISBN: 9781450333627. DOI: 10.1145/2858036.2858058. URL: https://doi.org/10.1145/2858036.2858058.

[91] Frank Elavsky, Lucas Nadolskis, and Dominik Moritz. “Data Navigator: An Accessibility-Centered Data Navigation Toolkit”. In: *IEEE Transactions on Visualization and Computer Graphics* (2023). URL: https://www.domoritz.de/papers/2023-DataNavigator-VIS.pdf.

[92] Wafa Elmannai and Khaled Elleithy. “Sensor-Based Assistive Devices for Visually-Impaired People: Current Status, Challenges, and Future Directions”. In: *Sensors* 17.3 (2017). ISSN: 1424-8220. DOI: 10.3390/s17030565. URL: https://www.mdpi.com/1424-8220/17/3/565.

[93] Christin Engel, Nadja Konrad, and Gerhard Weber. “TouchPen: Rich Interaction Technique for Audio-Tactile Charts by Means of Digital Pens”. In: *International Conference on Computers Helping People with Special Needs*. Springer. Lecco, Italy: Springer International Publishing, 2020, pp. 446–455.

[94] Christin Engel, Emma Franziska Müller, and Gerhard Weber. “SVGPlott: an accessible tool to generate highly adaptable, accessible audio-tactile charts for and from blind and visually impaired people”. In: *Proceedings of the 12th ACM International Conference on PErvasive Technologies Related to Assistive Environments*. PETRA ’19. Rhodes, Greece: Association for Computing Machinery, 2019, pp. 186–195. ISBN: 9781450362320. DOI: 10.1145/3316782.3316793. URL: https://doi.org/10.1145/3316782.3316793.

[95] Christin Engel, Karin Müller, Angela Constantinescu, Claudia Loitsch, Vanessa Petrausch, Gerhard Weber, and Rainer Stiefelhagen. “Travelling more independently: A Requirements Analysis for Accessible Journeys to Unknown Buildings for People with Visual Impairments”. In: *Proceedings of the 22nd International ACM SIGACCESS Conference on Computers and Accessibility*. ASSETS ’20. Virtual Event, Greece: Association for Computing Machinery, 2020. ISBN: 9781450371032. DOI: 10.1145/3373625.3417022. URL: https://doi.org/10.1145/3373625.3417022.

[96] Christin Engel and Gerhard Weber. “A User Study to Evaluate Tactile Charts with Blind and Visually Impaired People”. In: *Computers Helping People with Special Needs*. Ed. by Klaus Miesenberger and Georgios Kouroupetroglou. Cham: Springer International Publishing, 2018, pp. 177–184. ISBN: 978-3-319-94274-2.

[97] Christin Engel and Gerhard Weber. “Analysis of Tactile Chart Design”. In: *Proceedings of the 10th International Conference on PErvasive Technologies Related to Assistive Environments*. PETRA ’17. Island of Rhodes, Greece: Association for Computing Machinery, 2017, pp. 197–200. ISBN: 9781450352277. DOI: 10.1145/3056540.3064955. URL: https://doi.org/10.1145/3056540.3064955.

[98] Christin Engel and Gerhard Weber. “ATIM: Automated Generation of Interactive, Audio-Tactile Indoor Maps by Means of a Digital Pen”. In: *Computers Helping People with Special Needs*. Ed. by Klaus Miesenberger, Georgios Kouroupetroglou, Katerina Mavrou, Roberto Manduchi, Mario Covarrubias Rodriguez, and Petr Penáz. Cham: Springer International Publishing, 2022, pp. 123–133. ISBN: 978-3-031-08648-9. URL: https://doi.org/10.1007/978-3-031-08648-9_15.

[99] Christin Engel and Gerhard Weber. “Improve the Accessibility of Tactile Charts”. In: *Human-Computer Interaction - INTERACT 2017*. Ed. by Regina Bernhaupt, Girish Dalvi, Anirudha Joshi, Devanuj K. Balkrishan, Jacki O’Neill, and Marco Winckler. Cham: Springer International Publishing, 2017, pp. 187–195. ISBN: 978-3-319-67744-6.

[100] C. Engelstad, S. Malaier, S. B. O’Day, R. Sheffield, E. Schaller, D. Snow, L. Turner, and S. Walker. *Accessible Communities Analysis*. Louisville, KY, 2019. URL: https://archive.org/details/accessiblecommunitiesanalysis.

[101] Aluna Everitt. “Digital Fabrication Approaches for the Design and Development of Shape-Changing Displays”. English. PhD thesis. Lancaster University, 2020. DOI: 10.17635/lancaster/thesis/850. URL: https://doi.org/10.17635/lancaster/thesis/850.

[102] Danyang Fan, Alexa Fay Siu, Sile O’Modhrain, and Sean Follmer. “Constructive Visualization to Inform the Design and Exploration of Tactile Data Representations”. In: *Proceedings of the 22nd International ACM SIGACCESS Conference on Computers and Accessibility*. ASSETS ’20. Virtual Event, Greece: Association for Computing Machinery, 2020, pp. 1–4. ISBN: 9781450371032. DOI: 10.1145/3373625.3418027. URL: https://doi.org/10.1145/3373625.3418027.

[103] Danyang Fan, Alexa Fay Siu, Wing-Sum Adrienne Law, Raymond Ruihong Zhen, Sile O'Modhrain, and Sean Follmer. "Slide-Tone and Tilt-Tone: 1-DOF Haptic Techniques for Conveying Shape Characteristics of Graphs to Blind Users". In: *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems.* CHI '22. New Orleans, LA, USA: Association for Computing Machinery, 2022. ISBN: 9781450391573. DOI: 10.1145/3491102.3517790. URL: https://doi.org/10.1145/3491102.3517790.

[104] Selina Feitl, Julian Kreimeier, and Timo Götzelmann. "Accessible Electrostatic Surface Haptics: Towards an Interactive Audiotactile Map Interface for People With Visual Impairments". In: *Proceedings of the 15th International Conference on PErvasive Technologies Related to Assistive Environments.* PETRA '22. Corfu, Greece: Association for Computing Machinery, 2022, pp. 522–531. ISBN: 9781450396318. DOI: 10.1145/3529190.3534781. URL: https://doi.org/10.1145/3529190.3534781.

[105] Leo Ferres, Gitte Lindgaard, Livia Sumegi, and Bruce Tsuji. "Evaluating a Tool for Improving Accessibility to Charts and Graphs". In: *ACM Trans. Comput.-Hum. Interact.* 20.5 (Nov. 2013). ISSN: 1073-0516. DOI: 10.1145/2533682.2533683. URL: https://doi.org/10.1145/2533682.2533683.

[106] Alexander Fiannaca, Ilias Apostolopoulous, and Eelke Folmer. "Headlock: A Wearable Navigation Aid That Helps Blind Cane Users Traverse Large Open Spaces". In: *Proceedings of the 16th International ACM SIGACCESS Conference on Computers & Accessibility.* ASSETS '14. Rochester, New York, USA: Association for Computing Machinery, 2014, pp. 323–324. ISBN: 9781450327206. DOI: 10.1145/2661334.2661344. URL: https://doi.org/10.1145/2661334.2661344.

[107] The Document Foundation. *Draw | LibreOffice - Free Office Suite.* Website. (Accessed on 2023). 2017. URL: https://www.libreoffice.org/discover/draw/.

[108] Diamantino Freitas and Georgios Kouroupetroglou. "Speech technologies for blind and low vision persons". In: *Technology and Disability* 20.2 (2008), pp. 135–156.

[109] Ryoji Fukuda and Akihiro Miura. "Improvements and Evaluations of Tactile Graphical Viewer for the Visually Impaired". In: *ATCM* (2012). URL: https://atcm.mathandtech.org/EP2012/regular_papers/3472012_19918.pdf.

[110] Giovanni Fusco and Valerie S. Morash. "The Tactile Graphics Helper: Providing Audio Clarification for Tactile Graphics Using Machine Vision". In: *Proceedings of the 17th International ACM SIGACCESS Conference on Computers & Accessibility.* ASSETS '15. Lisbon, Portugal: Association for Computing Machinery, 2015, pp. 97–106. ISBN: 9781450334006. DOI: 10.1145/2700648.2809868. URL: https://doi.org/10.1145/2700648.2809868.

[111] Nadia Garcia-Hernandez, Nikos G. Tsagarakis, and Darwin G. Caldwell. "Feeling through Tactile Displays: A Study on the Effect of the Array Density and Size on the Discrimination of Tactile Patterns". In: *IEEE Transactions on Haptics* 4.2 (2011), pp. 100–110. DOI: 10.1109/TOH.2010.59. URL: https://doi.org/10.1109/TOH.2010.59.

[112] John A. Gardner and Vladimir Bulatov. “Scientific Diagrams Made Easy with IVEOTM”. In: *Computers Helping People with Special Needs*. Ed. by Klaus Miesenberger, Joachim Klaus, Wolfgang L. Zagler, and Arthur I. Karshmer. Berlin, Heidelberg: Springer Berlin Heidelberg, 2006, pp. 1243–1250. ISBN: 978-3-540-36021-6. DOI: 10.1007/11788713_179. URL: https://doi.org/10.1007/11788713_179.

[113] Andrea Gerino, Lorenzo Picinali, Cristian Bernareggi, Nicolò Alabastro, and Sergio Mascetti. “Towards Large Scale Evaluation of Novel Sonification Techniques for Non Visual Shape Exploration”. In: *Proceedings of the 17th International ACM SIGACCESS Conference on Computers & Accessibility*. ASSETS ’15. Lisbon, Portugal: Association for Computing Machinery, 2015, pp. 13–21. ISBN: 9781450334006. DOI: 10.1145/2700648.2809848. URL: https://doi.org/10.1145/2700648.2809848.

[114] Global Disability Innovation Hub. *Creating Refreshable Displays That Are Accessible to Blind and Visually Impaired People*. 2021. URL: https://www.disabilityinnovation.com/projects/refreshable-displays-for-blind-and-visually-impaired-people.

[115] Help Tech GmbH. *Graphic Window Professional (GWP)*. 2001. URL: https://www.helptech.de/.

[116] Inventivio GmbH. *Tactonom (The Tactile Graphics Display)*. 2023. URL: https://www.tactonom.com/en/tactonom/.

[117] Inventivio GmbH. *Tactonom Reader*. 2023. URL: https://www.tactonom.com/en/tactonom-reader/.

[118] David Gollasch, Christin Engel, Meinhardt Branig, and Gerhard Weber. “Towards Accessible Charts for Blind and Partially Sighted People”. In: *Mensch und Computer 2017 - Tagungsband*. Sept. 2017. URL: https://doi.org/10.18420/muc2017-mci-0338.

[119] Cagatay Goncu, Anuradha Madugalla, Simone Marinai, and Kim Marriott. “Accessible On-Line Floor Plans”. In: *Proceedings of the 24th International Conference on World Wide Web*. WWW ’15. Florence, Italy: International World Wide Web Conferences Steering Committee, 2015, pp. 388–398. ISBN: 9781450334693. DOI: 10.1145/2736277.2741660. URL: https://doi.org/10.1145/2736277.2741660.

[120] Cagatay Goncu and Kim Marriott. “GraVVITAS: Generic Multi-touch Presentation of Accessible Graphics”. In: *Human-Computer Interaction – INTERACT 2011*. Ed. by Pedro Campos, Nicholas Graham, Joaquim Jorge, Nuno Nunes, Philippe Palanque, and Marco Winckler. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, pp. 30–48. ISBN: 978-3-642-23774-4. URL: https://doi.org/10.1007/978-3-642-23774-4_5.

[121] Jenna L. Gorlewicz, Jennifer L. Tennison, Hari P. Palani, and Nicholas A. Giudice. “The Graphical Access Challenge for People with Visual Impairments: Positions and Pathways Forward”. In: *Interactive Multimedia*. Ed. by Dragan Cvetković. Rijeka: IntechOpen, 2018. Chap. 7. DOI: 10.5772/intechopen.82289. URL: https://doi.org/10.5772/intechopen.82289.

[122] Joshua Gorniak, Yoon Kim, Donglai Wei, and Nam Wook Kim. "VizAbility: Enhancing Chart Accessibility with LLM-based Conversational Interaction". In: *Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology*. UIST '24. Pittsburgh, PA, USA: Association for Computing Machinery, 2024. DOI: 10.1145/3654777.3676414. URL: https://doi.org/10.1145/3654777.3676414.

[123] Timo Götzelmann. "CapMaps: Capacitive Sensing 3D Printed Audio-Tactile Maps". In: *Computers Helping People with Special Needs*. Ed. by Klaus Miesenberger, Christian Bühler, and Petr Penaz. Cham: Springer International Publishing, 2016, pp. 146–152. ISBN: 978-3-319-41267-2. URL: https://doi.org/10.1007/978-3-319-41267-2_20.

[124] Timo Götzelmann. "LucentMaps: 3D Printed Audiovisual Tactile Maps for Blind and Visually Impaired People". In: *Proceedings of the 18th International ACM SIGACCESS Conference on Computers and Accessibility*. ASSETS '16. Reno, Nevada, USA: Association for Computing Machinery, 2016, pp. 81–90. ISBN: 9781450341240. DOI: 10.1145/2982142.2982163. URL: https://doi.org/10.1145/2982142.2982163.

[125] Timo Götzelmann, Julian Kreimeier, Johannes Schwabl, Pascal Karg, Christina Oumard, and Florian Büttner. "AmI-VR: An Accessible Building Information System as Case Study Towards the Applicability of Ambient Intelligence in Virtual Reality". In: *Proceedings of Mensch Und Computer 2021*. MuC '21. Ingolstadt, Germany: Association for Computing Machinery, 2021, pp. 597–600. ISBN: 9781450386456. DOI: 10.1145/3473856.3474032. URL: https://doi.org/10.1145/3473856.3474032.

[126] Timo Götzelmann and Klaus Winkler. "SmartTactMaps: A Smartphone-Based Approach to Support Blind Persons in Exploring Tactile Maps". In: *Proceedings of the 8th ACM International Conference on PErvasive Technologies Related to Assistive Environments*. PETRA '15. Corfu, Greece: Association for Computing Machinery, 2015. ISBN: 9781450334525. DOI: 10.1145/2769493.2769497. URL: https://doi.org/10.1145/2769493.2769497.

[127] Renan Guarese, Emma Pretty, Aidan Renata, Deb Polson, and Fabio Zambetta. "Exploring Audio Interfaces for Vertical Guidance in Augmented Reality via Hand-Based Feedback". In: *IEEE Transactions on Visualization and Computer Graphics* 30.5 (2024), pp. 2818–2828. DOI: 10.1109/TVCG.2024.3372040.

[128] Renan Guarese, Fabio Zambetta, and Ron van Schyndel. "Evaluating Micro-Guidance Sonification Methods in Manual Tasks for Blind and Visually Impaired People". In: *Proceedings of the 34th Australian Conference on Human-Computer Interaction*. OzCHI '22. Canberra, ACT, Australia: Association for Computing Machinery, 2023, pp. 260–271. DOI: 10.1145/3572921.3572929. URL: https://doi.org/10.1145/3572921.3572929.

[129] Tiago Guerreiro, Kyle Montague, João Guerreiro, Rafael Nunes, Hugo Nicolau, and Daniel J.V. Gonçalves. "Blind People Interacting with Large Touch Surfaces: Strategies for One-handed and Two-handed Exploration". In: *Proceedings of the 2015 International Conference on Interactive Tabletops & Surfaces*. ITS '15. Madeira, Portugal: Association for Computing Machinery, 2015, pp. 25–34. ISBN: 9781450338998. DOI: 10.1145/2817721.2817743. URL: https://doi.org/10.1145/2817721.2817743.

[130] René Gutschmidt, Maria Schiewe, Francis Zinke, and Helmut Jürgensen. "Haptic Emulation of Games: Haptic Sudoku for the Blind". In: *Proceedings of the 3rd International Conference on PErvasive Technologies Related to Assistive Environments*. PETRA '10. Samos, Greece: Association for Computing Machinery, 2010. ISBN: 9781450300711. DOI: 10.1145/1839294.1839297. URL: https://doi.org/10.1145/1839294.1839297.

[131] Mordechai Haklay and Patrick Weber. "OpenStreetMap: User-Generated Street Maps". In: *IEEE Pervasive Computing* 7.4 (2008), pp. 12–18. DOI: 10.1109/MPRV.2008.80.

[132] Sandra G. Hart and Lowell E. Staveland. "Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research". In: *Human Mental Workload*. Ed. by Peter A. Hancock and Najmedin Meshkati. Vol. 52. Advances in Psychology. Amsterdam, Holland: North-Holland, 1988, pp. 139–183. DOI: https://doi.org/10.1016/S0166-4115(08)62386-9. URL: https://www.sciencedirect.com/science/article/pii/S0166411508623869.

[133] Vincent Hayward, Oliver R. Astley, Manuel Cruz-Hernandez, Danny Grant, and Gabriel Robles-De-La-Torre. "Haptic interfaces and devices". In: *Sensor Review* 24 (2004), pp. 16–29. DOI: https://doi.org/10.1108/02602280410515770. URL: https://doi.org/10.1108/02602280410515770.

[134] Liang He, Zijian Wan, Leah Findlater, and Jon E. Froehlich. "TacTILE: A Preliminary Toolchain for Creating Accessible Graphics with 3D-Printed Overlays and Auditory Annotations". In: *Proceedings of the 19th International ACM SIGACCESS Conference on Computers and Accessibility*. ASSETS '17. Baltimore, Maryland, USA: Association for Computing Machinery, 2017, pp. 397–398. ISBN: 9781450349260. DOI: 10.1145/3132525.3134818. URL: https://doi.org/10.1145/3132525.3134818.

[135] Thomas T. Hewett, Ronald Baecker, Stuart Card, Tom Carey, Jean Gasen, Marilyn Mantei, Gary Perlman, Gary Strong, and William Verplank. *ACM SIGCHI Curricula for Human-Computer Interaction*. Tech. rep. New York, NY, USA: ., 1992. DOI: https://doi.org/10.1145/2594128. URL: https://doi.org/10.1145/2594128.

[136] Eve Hoggan, Andrew Crossan, Stephen A. Brewster, and Topi Kaaresoja. "Audio or tactile feedback: which modality when?" In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '09. Boston, MA, USA: Association for Computing Machinery, 2009, pp. 2253–2256. ISBN: 9781605582467. DOI: 10.1145/1518701.1519045. URL: https://doi.org/10.1145/1518701.1519045.

[137] Leona Holloway, Swamy Ananthanarayan, Matthew Butler, Madhuka Thisuri De Silva, Kirsten Ellis, Cagatay Goncu, Kate Stephens, and Kim Marriott. "Animations at Your Fingertips: Using a Refreshable Tactile Display to Convey Motion Graphics for People Who Are Blind or Have Low Vision". In: *Proceedings of the 24th International ACM SIGACCESS Conference on Computers and Accessibility*. ASSETS '22. Athens, Greece: Association for Computing Machinery, 2022. ISBN: 9781450392587. DOI: 10.1145/3517428.3544797. URL: https://doi.org/10.1145/3517428.3544797.

[138] Leona Holloway, Kim Marriott, and Matthew Butler. “Accessible Maps for the Blind: Comparing 3D Printed Models with Tactile Graphics”. In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI ’18. Montreal QC, Canada: Association for Computing Machinery, 2018, pp. 1–13. ISBN: 9781450356206. DOI: 10.1145/3173574.3173772. URL: https://doi.org/10.1145/3173574.3173772.

[139] Leona M Holloway, Cagatay Goncu, Alon Ilsar, Matthew Butler, and Kim Marriott. “Infosonics: Accessible Infographics for People who are Blind using Sonification and Voice”. In: *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI ’22. New Orleans, LA, USA: Association for Computing Machinery, 2022. ISBN: 9781450391573. DOI: 10.1145/3491102.3517465. URL: https://doi.org/10.1145/3491102.3517465.

[140] Samantha Horvath, John Galeotti, Bing Wu, Roberta Klatzky, Mel Siegel, and George Stetten. “FingerSight: Fingertip Haptic Sensing of the Visual Environment”. In: *IEEE Journal of Translational Engineering in Health and Medicine* 2 (2014), pp. 1–9. DOI: 10.1109/JTEHM.2014.2309343.

[141] HumanWare. *Monarch - Dynamic Tactile Device*. 2022. URL: https://www.humanware.com/en-usa/monarch.

[142] HumanWare. *Monarch - Technical Specification Document*. 2022. URL: https://www.humanware.com/Site/Files/a/06cc20404d351cbaa2520fcd0d5adc3/06771bbd1a209cae47b4e4727719 Technical%20Specification%20Document.pdf.

[143] Touch Graphics Inc. *T3 Tactile Tablet*. 2022. URL: https://www.touchgraphics.com/store/p/t3-tactile-tablet.

[144] Polymer Braille Inc. *Polymer Braille. Innovative Tech for the Blind*. 2017. URL: https://www.polymerbraille.com/.

[145] Dot Incorporation. *Dot Pad*. 2023. URL: https://pad.dotincorp.com/.

[146] International Organization for Standardization. *ISO 9241-210:2019 Ergonomics of human-system interaction — Part 210: Human-centred design for interactive systems*. International Standard. Edition 2. Aug. 2019. URL: https://www.iso.org/standard/77520.html.

[147] International Organization for Standardization. *ISO 9241-910:2011 Ergonomics of human-system interaction — Part 910: Framework for tactile and haptic interaction*. International Standard. Edition 1. July 2011. URL: https://www.iso.org/standard/51097.html.

[148] Mihail Ivanchev, Francis Zinke, and Ulrike Lucke. “Pre-journey Visualization of Travel Routes for the Blind on Refreshable Interactive Tactile Displays”. In: *Computers Helping People with Special Needs*. Ed. by Klaus Miesenberger, Deborah Fels, Dominique Archambault, Petr Peňáz, and Wolfgang Zagler. Cham: Springer International Publishing, 2014, pp. 81–88. ISBN: 978-3-319-08599-9. DOI: https://doi.org/10.1007/978-3-319-08599-9_13. URL: https://doi.org/10.1007/978-3-319-08599-9_13.

[149] Deepak Jagdish, Rahul Sawhney, Mohit Gupta, and Shreyas Nangia. “Sonic Grid: An Auditory Interface for the Visually Impaired to Navigate GUI-Based Environments”. In: *Proceedings of the 13th International Conference on Intelligent User Interfaces.* IUI ’08. Gran Canaria, Spain: Association for Computing Machinery, 2008, pp. 337–340. ISBN: 9781595939876. DOI: 10.1145/1378773.1378824. URL: https://doi.org/10.1145/1378773.1378824.

[150] Huang Jingyu, Dou Shilei, Xu Luning, and Han Li. “Modeling of Refreshing Rate and its Parametric Analysis of a Multi-lines Braille Display using Electrorheological Valves Matrix”. In: *2020 IEEE International Conference on Power, Intelligent Computing and Systems (ICPICS).* 2020, pp. 388–391. DOI: 10.1109/ICPICS50287.2020.9202336. URL: https://doi.org/10.1109/ICPICS50287.2020.9202336.

[151] Paul Johannesson and Erik Perjons. “Introduction”. In: *An Introduction to Design Science.* Cham: Springer International Publishing, 2021, pp. 1–21. ISBN: 978-3-030-78132-3. DOI: 10.1007/978-3-030-78132-3_1. URL: https://doi.org/10.1007/978-3-030-78132-3_1.

[152] Shakila Cherise S Joyner, Amalia Riegelhuth, Kathleen Garrity, Yea-Seul Kim, and Nam Wook Kim. “Visualization Accessibility in the Wild: Challenges Faced by Visualization Designers”. In: *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems.* CHI ’22. New Orleans, LA, USA: Association for Computing Machinery, 2022. ISBN: 9781450391573. DOI: 10.1145/3491102.3517630. URL: https://doi.org/10.1145/3491102.3517630.

[153] Crescentia Jung, Shubham Mehta, Atharva Kulkarni, Yuhang Zhao, and Yea-Seul Kim. “Communicating Visualizations without Visuals: Investigation of Visualization Alternative Text for People with Visual Impairments”. In: *IEEE Transactions on Visualization and Computer Graphics* 28.1 (2022), pp. 1095–1105. DOI: 10.1109/TVCG.2021.3114846.

[154] Jung-Il Jung and Jin-Soo Cho. “Design and implementation of real-time haptic display system”. In: *Journal of the Institute of Electronics Engineers of Korea CI* 48.2 (2011), pp. 1–8. URL: https://koreascience.kr/article/JAKO201112961960967.pdf.

[155] Jung-Il Jung, Heung-Gi Kim, and Jin-Soo Cho. “Design and Implementation of a Real-Time Education Assistive Technology System Based on Haptic Display to Improve Education Environment of Total Blindness People”. In: *The Journal of the Korea Contents Association* (Dec. 2011). DOI: 10.5392/jkca.2011.11.12.094. URL: https://doi.org/10.5392/JKCA.2011.11.12.094.

[156] Helmut Jürgensen and Christopher Power. “Information access for the blind–graphics, modes, interaction”. In: *Proceedings of GOTHI’05 Guidelines on Tactile and Haptic Interactions.* 2005, pp. 24–26. URL: https://userlab.usask.ca/GOTHI/Jurgensen%20-%20Powers.pdf.

[157] Amy Kalia, Rose Hopkins, David Jin, Lindsay Yazzolino, Svena Verma, Lotfi Merabet, Flip Phillips, and Pawan Sinha. "Perception of tactile graphics: Embossings versus cutouts". In: *Multisensory research* 27.2 (2014), pp. 111–125. DOI: 10.1163/22134808-00002450.

[158] P. Kammermeier and G. Schmidt. "Application-specific evaluation of tactile array displays for the human fingertip". In: *IEEE/RSJ International Conference on Intelligent Robots and Systems*. Vol. 3. 2002, 2937–2942 vol.3. DOI: 10.1109/IRDS.2002.1041718. URL: https://doi.org/10.1109/IRDS.2002.1041718.

[159] Shaun K. Kane, Meredith Ringel Morris, Annuska Z. Perkins, Daniel Wigdor, Richard E. Ladner, and Jacob O. Wobbrock. "Access Overlays: Improving Non-Visual Access to Large Touch Screens for Blind Users". In: *Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology*. UIST '11. Santa Barbara, California, USA: Association for Computing Machinery, 2011, pp. 273–282. ISBN: 9781450307161. DOI: 10.1145/2047196.2047232. URL: https://doi.org/10.1145/2047196.2047232.

[160] A. A. Karpov and R. M. Yusupov. "Multimodal Interfaces of Human–Computer Interaction". In: *Herald of the Russian Academy of Sciences* 88.1 (2018), pp. 67–74. ISSN: 1555-6492. DOI: 10.1134/S1019331618010094. URL: https://doi.org/10.1134/S1019331618010094.

[161] Jill Keeffe. "Psychosocial impact of vision impairment". In: *International Congress Series* 1282 (2005). Vision 2005, pp. 167–173. ISSN: 0531-5131. DOI: https://doi.org/10.1016/j.ics.2005.06.005. URL: https://www.sciencedirect.com/science/article/pii/S0531513105009908.

[162] Jeongyeon Kim, Yoonah Lee, and Inho Seo. "Math Graphs for the Visually Impaired: Audio Presentation of Elements of Mathematical Graphs". In: *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI EA '19. Glasgow, Scotland Uk: Association for Computing Machinery, 2019, pp. 1–6. ISBN: 9781450359719. DOI: 10.1145/3290607.3308452. URL: https://doi.org/10.1145/3290607.3308452.

[163] Joonyeong Kim, Byung-Kil Han, and Dong-Soo Kwon. "2D Braille Display Module Using Rotating Latch Structured Voice Coil Actuator". In: *Haptic Interaction*. Ed. by Hiroyuki Kajimoto, Dongjun Lee, Sang-Youn Kim, Masashi Konyo, and Ki-Uk Kyung. Singapore: Springer Singapore, 2019, pp. 223–225. ISBN: 978-981-13-3194-7. URL: https://doi.org/10.1007/978-981-13-3194-7_51.

[164] Joonyeong Kim, Byung-Kil Han, Dongbum Pyo, Semin Ryu, Hanbyeol Kim, and Dong-Soo Kwon. "Braille Display for Portable Device Using Flip-Latch Structured Electromagnetic Actuator". In: *IEEE Transactions on Haptics* 13.1 (2020), pp. 59–65. DOI: 10.1109/TOH.2019.2963858. URL: https://doi.org/10.1109/TOH.2019.2963858.

[165] N. W. Kim, S. C. Joyner, A. Riegelhuth, and Y. Kim. “Accessible Visualization: Design Space, Opportunities, and Challenges”. In: *Computer Graphics Forum* 40.3 (2021), pp. 173–188. DOI: https://doi.org/10.1111/cgf.14298. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/cgf.14298. URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/cgf.14298.

[166] Sang-Ho Kim, Kosuke Sekiyama, Toshio Fukuda, Kenji Tanaka, and Kouichi Itoigawa. “Development of Dynamically Re-formable Input Device in Tactile and Visual Interaction”. In: *2007 International Symposium on Micro-NanoMechatronics and Human Science*. 2007, pp. 544–549. DOI: 10.1109/MHS.2007.4420914. URL: https://doi.org/10.1109/MHS.2007.4420914.

[167] Seondae Kim, Eun-Soo Park, and Eun-Seok Ryu. “Multimedia Vision for the Visually Impaired through 2D Multiarray Braille Display”. In: *Applied Sciences* 9.5 (2019). ISSN: 2076-3417. DOI: 10.3390/app9050878. URL: https://www.mdpi.com/2076-3417/9/5/878.

[168] Seondae Kim, Yeongil Ryu, Jinsoo Cho, and Eun-Seok Ryu. “Towards Tangible Vision for the Visually Impaired through 2D Multiarray Braille Display”. In: *Sensors* 19.23 (2019). ISSN: 1424-8220. DOI: 10.3390/s19235319. URL: https://www.mdpi.com/1424-8220/19/23/5319.

[169] Makoto KOBAYASHI. “Learning Environment for Students with Visual Impairment”. In: *Journal of Japan Society for Fuzzy Theory and Intelligent Informatics* 32.3 (2020), pp. 62–68. DOI: 10.3156/jsoft.32.3_62. URL: https://doi.org/10.3156/jsoft.32.3_62.

[170] Makoto Kobayashi and Tetsuya Watanabe. “A Tactile Display System Equipped with a Pointing Device — MIMIZU”. In: *Computers Helping People with Special Needs*. Ed. by Klaus Miesenberger, Joachim Klaus, and Wolfgang Zagler. Berlin, Heidelberg: Springer Berlin Heidelberg, 2002, pp. 527–534. ISBN: 978-3-540-45491-5. URL: https://doi.org/10.1007/3-540-45491-8_100.

[171] Makoto Kobayashi and Tetsuya Watanabe. “Communication System for the Blind Using Tactile Displays and Ultrasonic Pens – MIMIZU”. In: *Computers Helping People with Special Needs*. Ed. by Klaus Miesenberger, Joachim Klaus, Wolfgang L. Zagler, and Dominique Burger. Berlin, Heidelberg: Springer Berlin Heidelberg, 2004, pp. 731–738. ISBN: 978-3-540-27817-7. URL: https://doi.org/10.1007/978-3-540-27817-7_109.

[172] Makoto Kobayashi and Tetsuya Watanabe. “Multimedia Communication System for the Blind”. In: *Intelligent Paradigms for Assistive and Preventive Healthcare*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2006, pp. 165–181. ISBN: 978-3-540-31763-0. DOI: 10.1007/11418337_6. URL: https://doi.org/10.1007/11418337_6.

[173] Wiebke Köhlmann and Ulrike Lucke. “Alternative Concepts for Accessible Virtual Classrooms for Blind Users”. In: *2015 IEEE 15th International Conference on Advanced Learning Technologies*. 2015, pp. 413–417. DOI: 10.1109/ICALT.2015.9. URL: https://doi.org/10.1109/ICALT.2015.9.

[174] Martin Kurze. "Methods for the computer-generated presentation of spatial objects for blind people on tactile media". Dissertation. Freie Universität Berlin, 1999. URL: http://dx.doi.org/10.17169/refubium-7178.

[175] Kari Kuutti. "Activity theory as a potential framework for human-computer interaction research". In: *Context and consciousness: Activity theory and human-computer interaction* 1744 (1996), pp. 9–22. URL: https://doi.org/10.7551/mitpress/2137.003.0006.

[176] Kari Kuutti and Liam Bannon. "Some Confusions at the Interface: Re-conceptualizing the "interface" problem". In: Human Jobs & Computer Interfaces. Amsterdam: North-Holland, 1991, pp. 3–19. URL: https://www.researchgate.net/publication/339446568_Some_Confusions_at_the_Interface_Re-conceptualizing_the_interface_problem.

[177] Kari Kuutti and Liam J. Bannon. "Searching for Unity among Diversity: Exploring the "Interface" Concept". In: *Proceedings of the INTERACT '93 and CHI '93 Conference on Human Factors in Computing Systems*. CHI '93. Amsterdam, The Netherlands: Association for Computing Machinery, 1993, pp. 263–268. ISBN: 0897915755. DOI: 10.1145/169059.169206. URL: https://doi.org/10.1145/169059.169206.

[178] McGill University - Shared Reality Lab. *IMAGE - Making internet graphics accessible through rich audio and touch*. 2022. URL: https://image.a11y.mcgill.ca/index.htm.

[179] UEC Shimojo Laboratory. *Hatic Display for Blind User*. July 2013. URL: http://www.rm.mce.uec.ac.jp/sjE/index.php?Hatic+Display+for+Blind+User.

[180] Daniel Pacheco Lacerda, Aline Dresch, Adriano Proença, and José Antonio Valle Antunes Júnior. "Design Science Research: método de pesquisa para a engenharia de produção". In: *Gestão & produção* 20 (2013), pp. 741–761. URL: https://doi.org/10.1590/S0104-530X2013005000014.

[181] Steven Landau and Karen Gourgey. "Development of a talking tactile tablet". In: *Information Technology and Disabilities* 7.2 (2001).

[182] Bongshin Lee, Eun Kyoung Choe, Petra Isenberg, Kim Marriott, and John Stasko. "Reaching Broader Audiences With Data Visualization". In: *IEEE Computer Graphics and Applications* 40.2 (2020), pp. 82–90. DOI: 10.1109/MCG.2020.2968244.

[183] Dayeon Lee and Jinsoo Cho. "Automatic Object Detection Algorithm-Based Braille Image Generation System for the Recognition of Real-Life Obstacles for Visually Impaired People". In: *Sensors* 22.4 (2022). ISSN: 1424-8220. DOI: 10.3390/s22041601. URL: https://www.mdpi.com/1424-8220/22/4/1601.

[184] Fabrizio Leo, Caterina Baccelliere, Aleksander Waszkielewicz, Elena Cocchi, and Luca Brayda. "Tactile Symbol Discrimination on a Small Pin-Array Display". In: *MAHCI'18*. Seoul, Republic of Korea: Association for Computing Machinery, 2018, pp. 9–15. ISBN: 9781450359801. DOI: 10.1145/3264856.3264858. URL: https://doi.org/10.1145/3264856.3264858.

[185] Fabrizio Leo, Elena Cocchi, and Luca Brayda. "The Effect of Programmable Tactile Displays on Spatial Learning Skills in Children and Adolescents of Different Visual Disability". In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 25.7 (2017), pp. 861–872. DOI: 10.1109/TNSRE.2016.2619742. URL: https://doi.org/10.1109/TNSRE.2016.2619742.

[186] Fabrizio Leo, Elisabetta Ferrari, Caterina Baccelliere, Juan Zarate, Herbert Shea, Elena Cocchi, Aleksander Waszkielewicz, and Luca Brayda. "Enhancing general spatial skills of young visually impaired people with a programmable distance discrimination training: a case control study". In: *Journal of NeuroEngineering and Rehabilitation* 16.1 (Aug. 2019), p. 108. ISSN: 1743-0003. DOI: 10.1186/s12984-019-0580-2. URL: https://doi.org/10.1186/s12984-019-0580-2.

[187] Fabrizio Leo, Carla Tinti, Silvia Chiesa, Roberta Cavaglià, Susanna Schmidt, Elena Cocchi, and Luca Brayda. "Improving spatial working memory in blind and sighted youngsters using programmable tactile displays". In: *SAGE Open Med* 6 (2018), p. 2050312118820028. DOI: 10.1177/2050312118820028. URL: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6299321/.

[188] Jingyi Li, Son Kim, Joshua A. Miele, Maneesh Agrawala, and Sean Follmer. "Editing Spatial Layouts through Tactile Templates for People with Visual Impairments". In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI '19. Glasgow, Scotland Uk: Association for Computing Machinery, 2019, pp. 1–11. ISBN: 9781450359702. DOI: 10.1145/3290605.3300436. URL: https://doi.org/10.1145/3290605.3300436.

[189] Smart Technology Limited. *ITACTI - Project outcome - Full Graphical Array 128x64 dots*. 2007. URL: https://www.smarttec.co.uk/news.htm.

[190] J.G. Linvill and J.C. Bliss. "A direct translation reading aid for the blind". In: *Proceedings of the IEEE* 54.1 (1966), pp. 40–51. DOI: 10.1109/PROC.1966.4572. URL: https://doi.org/10.1109/PROC.1966.4572.

[191] C. Loconsole, D. Leonardis, M. Gabardi, and A. Frisoli. "BrailleCursor: an Innovative Refreshable Braille Display Based on a Single Sliding Actuator and Simple Passive Pins". In: *2019 IEEE World Haptics Conference (WHC)*. 2019, pp. 139–144. DOI: 10.1109/WHC.2019.8816128. URL: https://doi.org/10.1109/WHC.2019.8816128.

[192] Power Contents Technology Co. Ltd. *Tactile Pro (WORDS' FIRST FOR BLIND DISPLAY)*. 2019. URL: http://www.powerct.kr/.

[193] Sofia Lundmark. "Design project failures: Outcomes and gains of participation in design". In: *Design Studies* 59 (2018). Participatory Design, pp. 77–94. ISSN: 0142-694X. DOI: https://doi.org/10.1016/j.destud.2017.07.002. URL: https://www.sciencedirect.com/science/article/pii/S0142694X17300492.

[194] Michał Maćkowski, Piotr Brzoza, Mateusz Kawulok, and Tomasz Knura. "Mobile e-Learning Platform for Audio-Tactile Graphics Presentation". In: *Computers Helping People with Special Needs*. Ed. by Klaus Miesenberger, Georgios Kouroupetroglou, Katerina Mavrou, Roberto Manduchi, Mario Covarrubias Rodriguez, and Petr Penáz. Cham: Springer International Publishing, 2022, pp. 82–91. ISBN: 978-3-031-08648-9.

[195] Michał Maćkowski, Piotr Brzoza, Mateusz Kawulok, Rafał Meisel, and Dominik Spinczyk. "Multimodal Presentation of Interactive Audio-Tactile Graphics Supporting the Perception of Visual Information by Blind People". In: *ACM Trans. Multimedia Comput. Commun. Appl.* 19.5s (June 2023). ISSN: 1551-6857. DOI: 10.1145/3586076. URL: https://doi.org/10.1145/3586076.

[196] Michał Maćkowski, Piotr Brzoza, and Dominik Spinczyk. "An alternative method of audio-tactile presentation of graphical information in mathematics adapted to the needs of blind". In: *International Journal of Human-Computer Studies* 179 (2023), p. 103122. ISSN: 1071-5819. DOI: https://doi.org/10.1016/j.ijhcs.2023.103122. URL: https://www.sciencedirect.com/science/article/pii/S1071581923001313.

[197] Michał Maćkowski, Mateusz Kawulok, Piotr Brzoza, Marceli Janczy, and Dominik Spinczyk. "An Alternative Audio-Tactile Method of Presenting Structural Information Contained in Mathematical Drawings Adapted to the Needs of the Blind". In: *Applied Sciences* 13.17 (2023). ISSN: 2076-3417. DOI: 10.3390/app13179989. URL: https://www.mdpi.com/2076-3417/13/17/9989.

[198] Michał Maćkowski, Katarzyna Rojewska, Mariusz Dzieciątko, Katarzyna Bielecka, Mateusz Bas, and Dominik Spinczyk. "Methods Supporting the Understanding of Structural Information by Blind People and Selected Aspects of Their Evaluation". In: *Information Technology in Biomedicine.* Ed. by Ewa Pietka, Pawel Badura, Jacek Kawa, and Wojciech Wieclawek. Cham: Springer International Publishing, 2021, pp. 303–315. ISBN: 978-3-030-49666-1. DOI: 10.1007/978-3-030-49666-1_24. URL: https://doi.org/10.1007/978-3-030-49666-1_24.

[199] Kim Marriott, Bongshin Lee, Matthew Butler, Ed Cutrell, Kirsten Ellis, Cagatay Goncu, Marti Hearst, Kathleen McCoy, and Danielle Albers Szafir. "Inclusive data visualization for people with disabilities: a call to action". In: *Interactions* 28.3 (Apr. 2021), pp. 47–51. ISSN: 1072-5520. DOI: 10.1145/3457875. URL: https://doi.org/10.1145/3457875.

[200] Sergio Mascetti, Lorenzo Picinali, Andrea Gerino, Dragan Ahmetovic, and Cristian Bernareggi. "Sonification of guidance data during road crossing for people with visual impairments or blindness". In: *International Journal of Human-Computer Studies* 85 (2016). Data Sonification and Sound Design in Interactive Systems, pp. 16–26. ISSN: 1071-5819. DOI: https://doi.org/10.1016/j.ijhcs.2015.08.003. URL: https://www.sciencedirect.com/science/article/pii/S1071581915001275.

[201] Giuseppe Melfi, Jean Baumgarten, Karin Müller, and Rainer Stiefelhagen. "An Audio-Tactile System for Visually Impaired People to Explore Indoor Maps". In: *Computers Helping People with Special Needs.* Ed. by Klaus Miesenberger, Georgios Kouroupetroglou, Katerina Mavrou, Roberto Manduchi, Mario Covarrubias Rodriguez, and Petr Penáz. Cham: Springer International Publishing, 2022, pp. 134–142. ISBN: 978-3-031-08648-9. URL: https://doi.org/10.1007/978-3-031-08648-9_16.

[202] Giuseppe Melfi, Karin Müller, Thorsten Schwarz, Gerhard Jaworek, and Rainer Stiefelhagen. "Understanding What You Feel: A Mobile Audio-Tactile System for Graphics Used at Schools with Students with Visual Impairment". In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: Association for Computing Machinery, 2020, pp. 1–12. ISBN: 9781450367080. URL: https://doi.org/10.1145/3313831.3376508.

[203] Giuseppe Melfi, Lukas Schölch, Thorsten Schwarz, Karin Müller, and Rainer Stiefelhagen. "Audio-Tactile Reader (ATR): Interaction Concepts for Students with Blindness to Explore Digital STEM Documents on a 2D Haptic Device". In: *2022 IEEE Haptics Symposium (HAPTICS)*. 2022, pp. 1–6. DOI: 10.1109/HAPTICS52432.2022.9765568. URL: https://doi.org/10.1109/HAPTICS52432.2022.9765568.

[204] Evan X Merz. "Sonifying Processing: The Beads Tutorial". In: *Internet: http://www.computermusicblog. com/SonifyingProcessing* 1 (2011), pp. 1–138.

[205] METEC AG. *Braille-großdisplay DMD 12060*. METEC AG. 1989.

[206] Meredith Ringel Morris, Jazette Johnson, Cynthia L. Bennett, and Edward Cutrell. "Rich Representations of Visual Content for Screen Reader Users". In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI '18. <conf-loc>, <city>Montreal QC</city>, <country>Canada</country>, </conf-loc>: Association for Computing Machinery, 2018, pp. 1–11. ISBN: 9781450356206. DOI: 10.1145/3173574.3173633. URL: https://doi.org/10.1145/3173574.3173633.

[207] Omar Moured, Sara Alzalabny, Anas Osman, Thorsten Schwarz, Karin Müller, and Rainer Stiefelhagen. "ChartFormer: A Large Vision Language Model for Converting Chart Images into Tactile Accessible SVGs". In: *Computers Helping People with Special Needs*. Ed. by Klaus Miesenberger, Petr Peňáz, and Makato Kobayashi. Cham: Springer Nature Switzerland, 2024, pp. 299–305. ISBN: 978-3-031-62846-7.

[208] Mukhriddin Mukhiddinov and Soon-Young Kim. "A Systematic Literature Review on the Automatic Creation of Tactile Graphics for the Blind and Visually Impaired". In: *Processes* 9.10 (2021). ISSN: 2227-9717. DOI: 10.3390/pr9101726. URL: https://www.mdpi.com/2227-9717/9/10/1726.

[209] Karin Müller, Christin Engel, Claudia Loitsch, Rainer Stiefelhagen, and Gerhard Weber. "Traveling More Independently: A Study on the Diverse Needs and Challenges of People with Visual or Mobility Impairments in Unfamiliar Indoor Environments". In: *ACM Trans. Access. Comput.* 15.2 (May 2022). ISSN: 1936-7228. DOI: 10.1145/3514255. URL: https://doi.org/10.1145/3514255.

[210] Ruth G Nagassa, Matthew Butler, Leona Holloway, Cagatay Goncu, and Kim Marriott. "3D Building Plans: Supporting Navigation by People Who Are Blind or Have Low Vision in Multi-Storey Buildings". In: *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. CHI '23. Hamburg, Germany: Association for Computing Machinery, 2023, pp. 1–19. ISBN: 9781450394215. DOI: 10.1145/3544548.3581389. URL: https://doi.org/10.1145/3544548.3581389.

[211] William M. Newman and Robert F. Sproull, eds. *Principles of Interactive Computer Graphics (2nd Ed.)* USA: McGraw-Hill, Inc., 1979. ISBN: 0070463387. DOI: https://doi.org/10.1145/2594128. URL: https://doi.org/10.1145/2594128.

[212] Donald A. Norman and Stephen W. Draper. *User Centered System Design; New Perspectives on Human-Computer Interaction.* USA: L. Erlbaum Associates Inc., 1986. ISBN: 0898597811.

[213] Braille Authority of North America (BANA). *Guidelines and Standards for Tactile Graphics, 2022.* https://www.brailleauthority.org/guidelines-and-standards-tactile-graphics. Accessed: 2025-02-15. 2022.

[214] Marcia K. O'Malley and Abhishek Gupta. "Chapter 2 - Haptic Interfaces". In: *HCI Beyond the GUI.* Ed. by Philip Kortum. Interactive Technologies. San Francisco: Morgan Kaufmann, 2008, pp. 25–73. ISBN: 978-0-12-374017-5. DOI: https://doi.org/10.1016/B978-0-12-374017-5.00002-X. URL: https://www.sciencedirect.com/science/article/pii/B978012374017500002X.

[215] Liam O'Sullivan, Lorenzo Picinali, Andrea Gerino, and Douglas Cawthorne. "A prototype audio-tactile map system with an advanced auditory display". In: *International Journal of Mobile Human Computer Interaction (IJMHCI)* 7.4 (2015), pp. 53–75. DOI: 10.4018/IJMHCI.2015100104.

[216] Sile O'Modhrain, Nicholas A. Giudice, John A. Gardner, and Gordon E. Legge. "Designing Media for Visually-Impaired Users of Refreshable Touch Displays: Possibilities and Pitfalls". In: *IEEE Transactions on Haptics* 8.3 (2015), pp. 248–257. DOI: 10.1109/TOH.2015.2466231. URL: https://doi.org/10.1109/TOH.2015.2466231.

[217] Hiroyuki Ohshima, Makoto Kobayashi, and Shigenobu Shimada. "Development of Blind Football Play-by-Play System for Visually Impaired Spectators: Tangible Sports". In: *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems.* CHI EA '21. Yokohama, Japan: Association for Computing Machinery, 2021. ISBN: 9781450380959. DOI: 10.1145/3411763.3451737. URL: https://doi.org/10.1145/3411763.3451737.

[218] Keita Ohshiro, Amy Hurst, and Luke DuBois. "Making Math Graphs More Accessible in Remote Learning: Using Sonification to Introduce Discontinuity in Calculus". In: *Proceedings of the 23rd International ACM SIGACCESS Conference on Computers and Accessibility.* ASSETS '21. Virtual Event, USA: Association for Computing Machinery, 2021. ISBN: 9781450383066. DOI: 10.1145/3441852.3476533. URL: https://doi.org/10.1145/3441852.3476533.

[219] Samuel Paré, Maxime Bleau, Ismaël Djerourou, Vincent Malotaux, Ron Kupers, and Maurice Ptito. "Spatial navigation with horizontally spatialized sounds in early and late blind individuals". In: *PLOS ONE* 16.2 (Feb. 2021), pp. 1–14. DOI: 10.1371/journal.pone.0247448. URL: https://doi.org/10.1371/journal.pone.0247448.

[220] Taekeun Park, Jungil Jung, and Jinsoo Cho. “A method for automatically translating print books into electronic Braille books”. In: *Science China Information Sciences* 59.7 (June 16, 2016), p. 072101. ISSN: 1869-1919. DOI: 10.1007/s11432-016-5575-z. URL: https://doi.org/10.1007/s11432-016-5575-z.

[221] Ken Peffers, Tuure Tuunanen, Marcus A. Rothenberger, and Samir Chatterjee. “A Design Science Research Methodology for Information Systems Research”. In: *Journal of Management Information Systems* 24.3 (2007), pp. 45–77. DOI: 10.2753/MIS0742-1222240302. eprint: https://doi.org/10.2753/MIS0742-1222240302. URL: https://doi.org/10.2753/MIS0742-1222240302.

[222] Helen Petrie, Chandra Harrison, and Sundeep Dev. “Describing images on the web: a survey of current practice and prospects for the future”. In: *Proceedings of Human Computer Interaction International (HCII)* 71.2 (2005).

[223] Piaf Tactile: Adaptive Technology. *PIAF Tactile Image Maker*. Herpo. 2025. URL: https://piaf-tactile.com/.

[224] Antti Pirhonen and Kai Tuuri. “In Search for an Integrated Design Basis for Audio and Haptics”. In: *Haptic and Audio Interaction Design*. Ed. by Antti Pirhonen and Stephen Brewster. Berlin, Heidelberg: Springer Berlin Heidelberg, 2008, pp. 81–90. ISBN: 978-3-540-87883-4.

[225] Benjamin Poppinga, Charlotte Magnusson, Martin Pielot, and Kirsten Rassmus-Gröhn. “TouchOver Map: Audio-Tactile Exploration of Interactive Maps”. In: *Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services*. MobileHCI ’11. Stockholm, Sweden: Association for Computing Machinery, 2011, pp. 545–550. ISBN: 9781450305419. DOI: 10.1145/2037373.2037458. URL: https://doi.org/10.1145/2037373.2037458.

[226] Christopher Power. “On the Accuracy of Tactile Displays”. In: *Computers Helping People with Special Needs*. Ed. by Klaus Miesenberger, Joachim Klaus, Wolfgang L. Zagler, and Arthur I. Karshmer. Berlin, Heidelberg: Springer Berlin Heidelberg, 2006, pp. 1155–1162. ISBN: 978-3-540-36021-6. DOI: https://doi.org/10.1007/11788713_167. URL: https://doi.org/10.1007/11788713_167.

[227] Denise Prescher. “Taktile Interaktion auf flächigen Brailledisplays”. PhD thesis. Technische Universität Dresden, 2016. URL: https://tu-dresden.de/ing/informatik/ai/mci/ressourcen/dateien/Dissertation_DenisePrescher.pdf?lang=en.

[228] Denise Prescher, Jens Bornschein, and Gerhard Weber. “Consistency of a Tactile Pattern Set”. In: *ACM Trans. Access. Comput.* 10.2 (Apr. 2017). ISSN: 1936-7228. DOI: 10.1145/3053723. URL: https://doi.org/10.1145/3053723.

[229] Denise Prescher, Jens Bornschein, and Gerhard Weber. “Production of Accessible Tactile Graphics”. In: *Computers Helping People with Special Needs*. Ed. by Klaus Miesenberger, Deborah Fels, Dominique Archambault, Petr Peňáz, and Wolfgang Zagler. Cham: Springer International Publishing, 2014, pp. 26–33. ISBN: 978-3-319-08599-9.

[230] Denise Prescher and Gerhard Weber. "Comparing Two Approaches of Tactile Zooming on a Large Pin-Matrix Device". In: *Human-Computer Interaction - INTERACT 2017*. Ed. by Regina Bernhaupt, Girish Dalvi, Anirudha Joshi, Devanuj K. Balkrishan, Jacki O'Neill, and Marco Winckler. Cham: Springer International Publishing, 2017, pp. 173–186. ISBN: 978-3-319-67744-6. DOI: https://doi.org/10.1007/978-3-319-67744-6_11. URL: https://doi.org/10.1007/978-3-319-67744-6_11.

[231] Denise Prescher and Gerhard Weber. "Locating Widgets in Different Tactile Information Visualizations". In: *Computers Helping People with Special Needs*. Ed. by Klaus Miesenberger, Christian Bühler, and Petr Penaz. Cham: Springer International Publishing, 2016, pp. 100–107. ISBN: 978-3-319-41267-2. DOI: https://doi.org/10.1007/978-3-319-41267-2_14.

[232] Denise Prescher, Gerhard Weber, and Martin Spindler. "A Tactile Windowing System for Blind Users". In: *Proceedings of the 12th International ACM SIGACCESS Conference on Computers and Accessibility*. ASSETS '10. Orlando, Florida, USA: Association for Computing Machinery, 2010, pp. 91–98. ISBN: 9781605588810. DOI: 10.1145/1878803.1878821. URL: https://doi.org/10.1145/1878803.1878821.

[233] ProBlind. *ProBlind (Open-source tactile graphics dataset)*. ProBlind. 2025. URL: https://share.problind.org/app/list.

[234] The Inkscape Project. *Inkscape Open source vector graphics editor*. Software Freedom Conservancy, 2025. URL: https://inkscape.org/.

[235] Maurice Ptito, Maxime Bleau, Ismaël Djerourou, Samuel Paré, Fabien C. Schneider, and Daniel-Robert Chebat. "Brain-Machine Interfaces to Assist the Blind". In: *Frontiers in Human Neuroscience* 15 (2021). ISSN: 1662-5161. DOI: 10.3389/fnhum.2021.638887. URL: https://www.frontiersin.org/articles/10.3389/fnhum.2021.638887.

[236] Andrzej Radecki, Michał Bujacz, Piotr Skulimowski, and Paweł Strumiłło. "Interactive sonification of images in serious games as an education aid for visually impaired children". In: *British Journal of Educational Technology* 51.2 (2020), pp. 473–497. DOI: https://doi.org/10.1111/bjet.12852. eprint: https://bera-journals.onlinelibrary.wiley.com/doi/pdf/10.1111/bjet.12852. URL: https://bera-journals.onlinelibrary.wiley.com/doi/abs/10.1111/bjet.12852.

[237] Gaspar Ramôa. "Classification of 2D refreshable tactile user interfaces". In: *Assistive Technology, Accessibility and (e) Inclusion, ICCHP-AAATE 2022* 01 (July 2022), pp. 186–192. DOI: 10.35011/icchp-aaate22-p1-24. URL: https://doi.org/10.35011/icchp-aaate22-p1-24.

[238] Gaspar Ramôa, Omar Moured, Karin Müller, Thorsten Schwarz, and Rainer Stiefelhagen. "Display and Use of Station Floor Plans on 2D Pin Matrix Displays for Blind and Visually Impaired People." In: *Proceedings of the 16th International Conference on PErvasive Technologies Related to Assistive Environments*. PETRA '23. Corfu, Greece: Association for Computing Machinery, 2023, pp. 254–258. DOI: 10.1145/3594806.3594839. URL: https://doi.org/10.1145/3594806.3594839.

[239] Gaspar Ramôa, Omar Moured, Thorsten Schwarz, Karin Müller, and Rainer Stiefelhagen. "Enabling People with Blindness to Distinguish Lines of Mathematical Charts with Audio-Tactile Graphic Readers". In: *Proceedings of the 16th International Conference on PErvasive Technologies Related to Assistive Environments.* PETRA '23. Corfu, Greece: Association for Computing Machinery, 2023, pp. 384–391. DOI: 10.1145/3594806.3594818. URL: https://doi.org/10.1145/3594806.3594818.

[240] Gaspar Ramôa, Vincent Schmidt, and Peter König. "Developing Dynamic Audio Navigation UIs to Pinpoint Elements in Tactile Graphics". In: *Multimodal Technologies and Interaction* 6.12 (2022). ISSN: 2414-4088. DOI: 10.3390/mti6120113. URL: https://www.mdpi.com/2414-4088/6/12/113.

[241] Gaspar Ramôa, Vincent Schmidt, Thorsten Schwarz, Rainer Stiefelhagen, and Peter König. "SONOICE! a Sonar–Voice dynamic user interface for assisting individuals with blindness and visual impairment in pinpointing elements in 2D tactile readers". In: *Frontiers in Rehabilitation Sciences* 5 (2024). ISSN: 2673-6861. DOI: 10.3389/fresc.2024.1368983. URL: https://www.frontiersin.org/journals/rehabilitation-sciences/articles/10.3389/fresc.2024.1368983.

[242] Hrishikesh Rao and Sile O'Modhrain. "Multimodal Representation of Complex Spatial Data". In: *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems.* CHI EA '19. Glasgow, Scotland Uk: Association for Computing Machinery, 2019, pp. 1–4. ISBN: 9781450359719. DOI: 10.1145/3290607.3313249. URL: https://doi.org/10.1145/3290607.3313249.

[243] Hrishikesh V. Rao and Sile O'Modhrain. "2Across: A Comparison of Audio-Tactile and Screen-Reader Based Representations of a Crossword Puzzle". In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems.* CHI '20. Honolulu, HI, USA: Association for Computing Machinery, 2020, pp. 1–12. ISBN: 9781450367080. DOI: 10.1145/3313831.3376207. URL: https://doi.org/10.1145/3313831.3376207.

[244] Orbit Research. *Graphiti – a Breakthrough in Non-Visual Access to All Forms of Graphical Information.* 2016. URL: http://www.orbitresearch.com/product/graphiti/.

[245] Orbit Research. *Graphiti Plus® – Interactive Tactile Graphics and Braille Computer.* 2022. URL: http://www.orbitresearch.com/product/graphiti-plus/.

[246] Orbit Research. *Orbit Research Introduces the Graphiti Plus Interactive Tactile Graphic and Braille Display.* 2022. URL: https://www.einnews.com/pr_news/565529646/orbit-research-introduces-the-graphiti-plus-interactive-tactile-graphic-and-braille-display.

[247] Orbit Research and America Printing House. *The World's First Affordable Refreshable Tactile Graphics Display.* 2016. URL: https://www.orbitresearch.com/orbit-research-and-american-printing-house-for-the-blind-announce-the-worlds-first-affordable-refreshable-tactile-graphics-display/.

[248] Hannah Ritchie, Max Roser, and Pablo Rosado. "Renewable Energy". In: *Our World in Data* -.- (2020), p. 1. URL: https://ourworldindata.org/renewable-energy.

[249] John Roberts. "NIST Refreshable Tactile Graphic Display: A New Low-Cost Technology". In: *Proceedings of the 2004 CSUN Conference on Technology and Persons with Disabilities.* National Institute of Standards, Technology (NIST) and National Federation of the Blind (NFB). Los Angeles, CA, USA, 2004. URL: http://www.csun.edu/~hfdss006/conf/2004/proceedings/152.htm.

[250] John Roberts, Oliver Slattery, David Kardos, and Brett Swope. "New Technology Enables Many-Fold Reduction in the Cost of Refreshable Braille Displays". In: *Proceedings of the Fourth International ACM Conference on Assistive Technologies.* Assets '00. Arlington, Virginia, USA: Association for Computing Machinery, 2000, pp. 42–49. ISBN: 1581133138. DOI: 10.1145/354324.354335. URL: https://doi.org/10.1145/354324.354335.

[251] John Roberts, Oliver Slattery, James O'Doherty, and Tracy Comstock. "37.2: A New Refreshable Tactile Graphic Display Technology for the Blind and Visually Impaired". In: *SID Symposium Digest of Technical Papers* 34.1 (2003), pp. 1148–1151. DOI: https://doi.org/10.1889/1.1832491. eprint: https://sid.onlinelibrary.wiley.com/doi/pdf/10.1889/1.1832491. URL: https://sid.onlinelibrary.wiley.com/doi/abs/10.1889/1.1832491.

[252] Toni Robertson and Jesper Simonsen. "Challenges and Opportunities in Contemporary Participatory Design". In: *Design Issues* 28.3 (2012), pp. 3–9. ISSN: 07479360, 15314790. URL: http://www.jstor.org/stable/23273834 (visited on 02/26/2025).

[253] Martin Rotard. "Standardized Computer Graphics Markup Languages for Interactive Systems". PhD thesis. Universität Stuttgart, Fakultät Informatik, Elektrotechnik und Informationstechnik, 2005. URL: http://dx.doi.org/10.18419/opus-2562.

[254] Martin Rotard, Sven Knödler, and Thomas Ertl. "A Tactile Web Browser for the Visually Disabled". In: *Proceedings of the Sixteenth ACM Conference on Hypertext and Hypermedia.* HYPERTEXT '05. Salzburg, Austria: Association for Computing Machinery, 2005, pp. 15–22. ISBN: 1595931686. DOI: 10.1145/1083356.1083361. URL: https://doi.org/10.1145/1083356.1083361.

[255] Martin Rotard, Christiane Taras, and Thomas Ertl. "Tactile Web Browsing for Blind People". In: *Multimedia Tools and Applications* 37.1 (Mar. 2008), pp. 53–69. ISSN: 1573-7721. DOI: 10.1007/s11042-007-0170-3. URL: https://doi.org/10.1007/s11042-007-0170-3.

[256] Noel H. Runyan and Deane B. Blazie. "The continuing quest for the 'Holy Braille' of tactile displays". In: *Nano-Opto-Mechanical Systems (NOMS).* Ed. by Jaume Esteve, Eugene M. Terentjev, and Eva M. Campo. Vol. 8107. International Society for Optics and Photonics. SPIE, 2011, 81070G. DOI: 10.1117/12.897382. URL: https://doi.org/10.1117/12.897382.

[257] K. Salisbury, F. Conti, and F. Barbagli. "Haptic rendering: introductory concepts". In: *IEEE Computer Graphics and Applications* 24.2 (2004), pp. 24–32. DOI: 10.1109/MCG.2004.1274058. URL: https://doi.ieeecomputersociety.org/10.1109/MCG.2004.10030.

[258] Jeff Sauro and James R Lewis. *Quantifying the User Experience: Practical Statistics for User Research.* Boston: Morgan Kaufmann, 2016.

[259] Maria Schiewe, Wiebke Köhlmann, Oliver Nadig, and Gerhard Weber. "What You Feel Is What You Get: Mapping GUIs on Planar Tactile Displays". In: *Universal Access in Human-Computer Interaction. Intelligent and Ubiquitous Interaction Environments.* Ed. by Constantine Stephanidis. Berlin, Heidelberg: Springer Berlin Heidelberg, 2009, pp. 564–573. ISBN: 978-3-642-02710-9. DOI: https://doi.org/10.1007/978-3-642-02710-9_63. URL: https://doi.org/10.1007/978-3-642-02710-9_63.

[260] Jan Schmalfuß-Schwarz, Christin Engel, and Gerhard Weber. "Supporting Independent Travelling for People with Visual Impairments in Buildings by Harmonizing Maps on Embossed Paper and Pin-Matrix Devices for Accessible Info-Points". In: *Computers Helping People with Special Needs.* Ed. by Klaus Miesenberger, Georgios Kouroupetroglou, Katerina Mavrou, Roberto Manduchi, Mario Covarrubias Rodriguez, and Petr Penáz. Cham: Springer International Publishing, 2022, pp. 143–152. ISBN: 978-3-031-08648-9.

[261] Michael Schmidt and Gerhard Weber. "Enhancing Single Touch Gesture Classifiers to Multitouch Support". In: *Computers Helping People with Special Needs.* Ed. by Klaus Miesenberger, Joachim Klaus, Wolfgang Zagler, and Arthur Karshmer. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010, pp. 490–497. ISBN: 978-3-642-14100-3. DOI: https://doi.org/10.1007/978-3-642-14100-3_73. URL: https://doi.org/10.1007/978-3-642-14100-3_73.

[262] Michael Schmidt and Gerhard Weber. "Multitouch Haptic Interaction". In: *Universal Access in Human-Computer Interaction. Intelligent and Ubiquitous Interaction Environments.* Ed. by Constantine Stephanidis. Berlin, Heidelberg: Springer Berlin Heidelberg, 2009, pp. 574–582. ISBN: 978-3-642-02710-9. DOI: https://doi.org/10.1007/978-3-642-02710-9_64. URL: https://doi.org/10.1007/978-3-642-02710-9_64.

[263] Vincent Schmidt, Sabine U. König, Rabia Dilawar, Tracy Sánchez Pacheco, and Peter König. "Improved Spatial Knowledge Acquisition through Sensory Augmentation". In: *Brain Sciences* 13.5 (2023). ISSN: 2076-3425. DOI: 10.3390/brainsci13050720. URL: https://www.mdpi.com/2076-3425/13/5/720.

[264] Bernhard Schmitz and Thomas Ertl. "Interactively Displaying Maps on a Tactile Graphics Display". In: *CEUR Workshop Proceedings.* Vol. 888. 2012. URL: https://api.semanticscholar.org/CorpusID:14894690.

[265] Thorsten Schwarz, Giuseppe Melfi, Stefan Scheiffele, and Rainer Stiefelhagen. "Interface for Automatic Tactile Display of Data Plots". In: *Computers Helping People with Special Needs.* Ed. by Klaus Miesenberger, Georgios Kouroupetroglou, Katerina Mavrou, Roberto Manduchi, Mario Covarrubias Rodriguez, and Petr Penáz. Cham: Springer International Publishing, 2022, pp. 73–81. ISBN: 978-3-031-08648-9. DOI: https://doi.org/10.1007/978-3-031-08648-9_10. URL: https://doi.org/10.1007/978-3-031-08648-9_10.

[266] W Schweikhardt. *Klöper," Rechnerunterstützte aufbereitung von bildshirmtext-grafiken in eine tastbare darstellung", Institut für Informatik Universität Stuttgart.* 1984.

[267] Waltraud Schweikhardt. "Interaktives erkunden tastbarer grafiken durch blinde". In: *Software-Erqonomie '85: Human-Computer Interaction.* Stuttgart: BGTeubner, 1985, pp. 366–375. ISBN: 3-519-02443-8. DOI: https://dl.acm.org/doi/10.5555/646638.700523. URL: https://dl.gi.de/items/4647604c-b501-4839-86cc-fc000c477ae7.

[268] Hasti Seifi. "Graphical User Interfaces for Blind Users: An Overview of Haptic Devices". In: *CPSC554m: Assignment 1.* 2013. URL: https://www.cs.ubc.ca/~cs554m/Winter2012/assignment1/HastiSefi_visual_impairments_report.pdf.

[269] Olivia R. Shaw and Jodi A. Hadden-Perilla. "TactViz: A VMD Plugin for Tactile Visualization of Protein Structures". In: *Journal of Science Education for Students with Disabilities* 23.1 (2020), Article 14. DOI: 10.14448/jsesd.12.0015. URL: https://scholarworks.rit.edu/jsesd/vol23/iss1/14.

[270] Shigenobu Shimada, Haruka Murase, Suguru Yamamoto, Yusuke Uchida, Makoto Shimojo, and Yutaka Shimizu. "Development of Directly Manipulable Tactile Graphic System with Audio Support Function". In: *Computers Helping People with Special Needs.* Ed. by Klaus Miesenberger, Joachim Klaus, Wolfgang Zagler, and Arthur Karshmer. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010, pp. 451–458. ISBN: 978-3-642-14100-3. DOI: https://doi.org/10.1007/978-3-642-14100-3_68. URL: https://doi.org/10.1007/978-3-642-14100-3_68.

[271] Shigenobu Shimada, Suguru Yamamoto, Yusuke Uchida, Masami Shinohara, Yutaka Shimizu, and Makoto Shimojo. "Development for an interactive communication display for blind computer users". In: *RO-MAN 2009 - The 18th IEEE International Symposium on Robot and Human Interactive Communication.* 2009, pp. 448–453. DOI: 10.1109/ROMAN.2009.5326304. URL: https://doi.org/10.1109/ROMAN.2009.5326304.

[272] Shigenobu Shimada, Suguru Yamamoto, Yusuke Uchida, Masami Shinohara, Yutaka Shimizu, and Makoto Shimojo. "New design for a dynamic tactile graphic system for blind computer users". In: *2008 SICE Annual Conference.* 2008, pp. 1474–1477. DOI: 10.1109/SICE.2008.4654891. URL: https://doi.org/10.1109/SICE.2008.4654891.

[273] M. Shimojo, M. Shinohara, and Y. Fukui. "Human shape recognition performance for 3D tactile display". In: *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans* 29.6 (1999), pp. 637–644. DOI: 10.1109/3468.798067. URL: https://doi.org/10.1109/3468.798067.

[274] Mathieu Simonnet. "Smart Map Augmented: Exploring and Learning Maritime Audio-Tactile Maps without Vision: The Issue of Finger or Marker Tracking". In: *Multimodal Technologies and Interaction* 6.8 (2022). ISSN: 2414-4088. DOI: 10.3390/mti6080066. URL: https://www.mdpi.com/2414-4088/6/8/66.

[275] Alexa F. Siu, Danyang Fan, Gene S-H Kim, Hrishikesh V. Rao, Xavier Vazquez, Sile O'Modhrain, and Sean Follmer. "COVID-19 highlights the issues facing blind and visually impaired people in accessing data on the web". In: *Proceedings of the 18th International Web for All Conference*. W4A '21. Ljubljana, Slovenia: Association for Computing Machinery, 2021. ISBN: 9781450382120. DOI: 10.1145/3430263.3452432. URL: https://doi.org/10.1145/3430263.3452432.

[276] Zoé Esmeralda Sobota, Ann-Christin Freese, Thorsten Schwarz, and Karin Müller. "Towards Establishing a Description Standard of Mathematical Function Graphs for People with Blindness". In: *Computers Helping People with Special Needs*. Ed. by Klaus Miesenberger, Petr Peňáz, and Makoto Kobayashi. Cham: Springer Nature Switzerland, 2024, pp. 313–321. ISBN: 978-3-031-62846-7.

[277] Martin Spindler, Michael Kraus, and Gerhard Weber. "A Graphical Tactile Screen-Explorer". In: *Computers Helping People with Special Needs*. Ed. by Klaus Miesenberger, Joachim Klaus, Wolfgang Zagler, and Arthur Karshmer. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010, pp. 474–481. ISBN: 978-3-642-14100-3. DOI: https://doi.org/10.1007/978-3-642-14100-3_71. URL: https://doi.org/10.1007/978-3-642-14100-3_71.

[278] National Institute of Standards and Technology. *NIST 'Pins' Down Imaging System for the Blind*. July 2002. URL: https://www.nist.gov/news-events/news/2002/09/nist-pins-down-imaging-system-blind.

[279] Anthony Steed, Eyal Ofek, Mike Sinclair, and Mar Gonzalez-Franco. "A Mechatronic Shape Display Based on Auxetic Materials". In: *Nature Communications* 12.1 (Aug. 2021), p. 4758. DOI: 10.1038/s41467-021-24974-0. URL: https://doi.org/10.1038/s41467-021-24974-0.

[280] Debbie Stone, Caroline Jarrett, Mark Woodroffe, and Shailey Minocha. *User interface design and evaluation*. Elsevier, 2005.

[281] Julian Striegl, Julius Felchow, Claudia Loitsch, and Gerhard Weber. "Accessible Indoor Orientation Support by Landmark-Based Navigation". In: *Universal Access in Human-Computer Interaction*. Ed. by Margherita Antona and Constantine Stephanidis. Cham: Springer Nature Switzerland, 2023, pp. 510–524. ISBN: 978-3-031-35681-0. URL: https://doi.org/10.1007/978-3-031-35681-0_34.

[282] Julian Striegl, Claudia Loitsch, Emma F. Etzold, and Gerhard Weber. "Mapable: Accessible Web-Based Indoor Maps for People with Diverse Interaction and Information Needs". In: *Universal Access in Human-Computer Interaction*. Ed. by Margherita Antona and Constantine Stephanidis. Cham: Springer Nature Switzerland, 2024, pp. 100–111. ISBN: 978-3-031-60881-0.

[283] Julian Striegl, Claudia Loitsch, Jan Schmalfuss-Schwarz, and Gerhard Weber. "Analysis of Indoor Maps Accounting the Needs of People with Impairments". In: *Computers Helping People with Special Needs*. Ed. by Klaus Miesenberger, Roberto Manduchi, Mario Covarrubias Rodriguez, and Petr Peňáz. Cham: Springer International Publishing, 2020, pp. 305–314. ISBN: 978-3-030-58805-2.

[284] Irene Sturm, Maria Schiewe, Wiebke Köhlmann, and Helmut Jürgensen. "Communicating through Gestures without Visual Feedback". In: *Proceedings of the 2nd International Conference on PErvasive Technologies Related to Assistive Environments*. PETRA '09. Corfu, Greece: Association for Computing Machinery, 2009. ISBN: 9781605584096. DOI: 10.1145/1579114.1579129. URL: https://doi.org/10.1145/1579114.1579129.

[285] Ryo Suzuki, Abigale Stangl, Mark D. Gross, and Tom Yeh. "FluxMarker: Enhancing Tactile Graphics with Dynamic Tactile Markers". In: *Proceedings of the 19th International ACM SIGACCESS Conference on Computers and Accessibility*. ASSETS '17. Baltimore, Maryland, USA: Association for Computing Machinery, 2017, pp. 190–199. ISBN: 9781450349260. DOI: 10.1145/3132525.3132548. URL: https://doi.org/10.1145/3132525.3132548.

[286] Marzia Taibbi, Cristian Bernareggi, Andrea Gerino, Dragan Ahmetovic, and Sergio Mascetti. "AudioFunctions: Eyes-Free Exploration of Mathematical Functions on Tablets". In: *Computers Helping People with Special Needs*. Ed. by Klaus Miesenberger, Deborah Fels, Dominique Archambault, Petr Peňáz, and Wolfgang Zagler. Cham: Springer International Publishing, 2014, pp. 537–544. ISBN: 978-3-319-08596-8.

[287] NOBORU TAKAGI, TAKASHI SUZUKI, and TOMOYUKI ARAKI. "Development of a Drawing Assistant System for Blind Users Using an Object-Oriented Graphic Description Language". In: *2020 International Conference on Machine Learning and Cybernetics (ICMLC)*. 2020, pp. 88–93. DOI: 10.1109/ICMLC51923.2020.9469041. URL: https://doi.org/10.1109/ICMLC51923.2020.9469041.

[288] Christiane Taras. "Presentation and interaction techniques for the efficient use of graphical user interfaces by blind and visually impaired". PhD thesis. Universität Stuttgart, 2011. URL: http://dx.doi.org/10.18419/opus-2704.

[289] Christiane Taras and Thomas Ertl. "Interaction with Colored Graphical Representations on Braille Devices". In: *Universal Access in Human-Computer Interaction. Addressing Diversity*. Ed. by Constantine Stephanidis. Berlin, Heidelberg: Springer Berlin Heidelberg, 2009, pp. 164–173. ISBN: 978-3-642-02707-9. DOI: https://doi.org/10.1007/978-3-642-02707-9_18. URL: https://doi.org/10.1007/978-3-642-02707-9_18.

[290] Christiane Taras, Michael Raschke, Thomas Schlegel, Thomas Ertl, Denise Prescher, and Gerhard Weber. "Improving Screen Magnification Using the HyperBraille Multiview Windowing Technique". In: *Computers Helping People with Special Needs*. Ed. by Klaus Miesenberger, Joachim Klaus, Wolfgang Zagler, and Arthur Karshmer. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010, pp. 506–512. ISBN: 978-3-642-14100-3. DOI: https://doi.org/10.1007/978-3-642-14100-3_75. URL: https://doi.org/10.1007/978-3-642-14100-3_75.

[291] Bristol Braille Technology. *Canute 360*. 2019. URL: https://bristolbraille.org/about-canute/.

[292] Bristol Braille Technology. *Canute 360 Technical Specification*. 2023. URL: https://bristolbraille.org/canute-360-support/support-Canute-360-Technical-Specification.htm.

[293] Bristol Braille Technology. *Canute Console*. 2019. URL: https://bristolbraille.org/about-canute-console-the-next-generation-in-braille/.

[294] Ender Tekin and James M. Coughlan. "A Mobile Phone Application Enabling Visually Impaired Users to Find and Read Product Barcodes". In: *Proceedings of the 12th International Conference on Computers Helping People with Special Needs*. ICCHP'10. Vienna, Austria: Springer-Verlag, 2010, pp. 290–295. ISBN: 3642140998.

[295] John R Thompson, Jesse J Martinez, Alper Sarikaya, Edward Cutrell, and Bongshin Lee. "Chart Reader: Accessible Visualization Experiences Designed with Screen Reader Users". In: *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. CHI '23. Hamburg, Germany: Association for Computing Machinery, 2023. ISBN: 9781450394215. DOI: 10.1145/3544548.3581186. URL: https://doi.org/10.1145/3544548.3581186.

[296] Brianna J. Tomlinson, Jared Batterman, Yee Chieh Chew, Ashley Henry, and Bruce N. Walker. "Exploring Auditory Graphing Software in the Classroom: The Effect of Auditory Graphs on the Classroom Environment". In: *ACM Trans. Access. Comput.* 9.1 (Nov. 2016). ISSN: 1936-7228. DOI: 10.1145/2994606. URL: https://doi.org/10.1145/2994606.

[297] Alessia Tonelli, Monica Gori, and Luca Brayda. "The Influence of Tactile Cognitive Maps on Auditory Space Perception in Sighted Persons". In: *Frontiers in Psychology* 7 (2016). ISSN: 1664-1078. DOI: 10.3389/fpsyg.2016.01683. URL: https://www.frontiersin.org/articles/10.3389/fpsyg.2016.01683.

[298] Hsin-Ruey Tsai, Yuan-Chia Chang, Tzu-Yun Wei, Chih-An Tsao, Xander Chin-yuan Koo, Hao-Chuan Wang, and Bing-Yu Chen. "GuideBand: Intuitive 3D Multilevel Force Guidance on a Wristband in Virtual Reality". In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. CHI '21. Yokohama, Japan: Association for Computing Machinery, 2021. ISBN: 9781450380966. DOI: 10.1145/3411764.3445262. URL: https://doi.org/10.1145/3411764.3445262.

[299] UCL, IIT Delhi, and Global Disability Innovation Hub. *Tacilia. World's first Voice Controlled Tactile User Interface*. 2021. URL: https://www.hellotacilia.com/home.

[300] UK Association for Accessible Formats (UKAAF). *Standard Dimensions for the UK Braille Cell*. 2017. URL: https://www.ukaaf.org/wp-content/uploads/2020/03/Braille-Standard-Dimensions.pdf.

[301] De Montfort University, Smart Technology Group Limited (SMART), Kaunas University of Technology (KUT), Metec Ingenieur-AG Medizintechnik-Feinwerktechnik (METEC AG), and Associazione Nazionale Subvedenti (ANS). *ITACTI IST - 2001 - 32240 Smart Interactive Tactile Interface Effecting Graphical Display for the Visually Impaired: DELIVERABLE D2.3 Device Performance and Operation*. Tech. rep. 1. De Montfort University, Jan. 2006. URL: https://www.smarttec.co.uk/itacti/deliverables/d2.3.pdf.

[302] De Montfort University, Smart Technology Group Limited (SMART), Kaunas University of Technology (KUT), Metec Ingenieur-AG Medizintechnik-Feinwerktechnik (METEC AG), and Associazione Nazionale Subvedenti (ANS). *ITACTI IST - 2001 - 32240 Smart Interactive Tactile Interface Effecting Graphical Display for the Visually Impaired: DELIVERABLE D6.2 and D6.3 Technical Verification Report.* Tech. rep. 1. De Montfort University, Dec. 2005. URL: https://www.smarttec.co.uk/itacti/deliverables/D6.3.pdf.

[303] De Montfort University, Smart Technology Group Limited (SMART), Kaunas University of Technology (KUT), Metec Ingenieur-AG Medizintechnik-Feinwerktechnik (METEC AG), and Associazione Nazionale Subvedenti (ANS). *ITACTI IST - 2001 - 32240 Smart Interactive Tactile Interface Effecting Graphical Display for the Visually Impaired: DELIVERABLE D7.4 Final Report.* Tech. rep. 1. De Montfort University, Dec. 2005. URL: https://www.smarttec.co.uk/itacti/deliverables/Final%20report.pdf.

[304] Vikas Upadhyay, Tigmanshu Bhatnagar, Catherine Holloway, P. V. M. Rao, and M. Balakrishnan. "Can Route Previews Amplify Building Orientation for People with Visual Impairment?" In: *Computers Helping People with Special Needs.* Ed. by Klaus Miesenberger, Georgios Kouroupetroglou, Katerina Mavrou, Roberto Manduchi, Mario Covarrubias Rodriguez, and Petr Penáz. Cham: Springer International Publishing, 2022, pp. 187–196. ISBN: 978-3-031-08648-9.

[305] Marynel Vázquez and Aaron Steinfeld. "Helping Visually Impaired Users Properly Aim a Camera". In: *Proceedings of the 14th International ACM SIGACCESS Conference on Computers and Accessibility.* ASSETS '12. Boulder, Colorado, USA: Association for Computing Machinery, 2012, pp. 95–102. ISBN: 9781450313216. DOI: 10.1145/2384916.2384934. URL: https://doi.org/10.1145/2384916.2384934.

[306] Fernando Vidal-Verdú and M. Hafez. "Graphical Tactile Displays for Visually-Impaired People". In: *IEEE transactions on neural systems and rehabilitation engineering : a publication of the IEEE Engineering in Medicine and Biology Society* 15 (Apr. 2007), pp. 119–30. DOI: 10.1109/TNSRE.2007.891375. URL: https://doi.org/10.1109/TNSRE.2007.891375.

[307] Visio. *SenseMath: Making mathematical functions audible.* Accessed: 2025-02-15. 2021. URL: https://www.visio.org/sensemath.

[308] Thorsten Völkel, Gerhard Weber, and Ulrich Baumann. "Tactile Graphics Revised: The Novel BrailleDis 9000 Pin-Matrix Device with Multitouch Input". In: *ICCHP.* Vol. 5105. July 2008, pp. 835–842. ISBN: 978-3-540-70539-0. DOI: 10.1007/978-3-540-70540-6_124. URL: https://link.springer.com/chapter/10.1007/978-3-540-70540-6_124.

[309] Julie M. Walker, Nabil Zemiti, Philippe Poignet, and Allison M. Okamura. "Holdable Haptic Device for 4-DOF Motion Guidance". In: *2019 IEEE World Haptics Conference (WHC).* Vol. -. 2019, pp. 109–114.

[310] Steven Wall and Stephen Brewster. "Feeling what you hear: tactile feedback for navigation of audio graphs". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '06. Montréal, Québec, Canada: Association for Computing Machinery, 2006, pp. 1123–1132. ISBN: 1595933727. DOI: 10.1145/1124772.1124941. URL: https://doi.org/10.1145/1124772.1124941.

[311] Xiyue Wang, Seita Kayukawa, Hironobu Takagi, and Chieko Asakawa. "TouchPilot: Designing a Guidance System That Assists Blind People in Learning Complex 3D Structures". In: *Proceedings of the 25th International ACM SIGACCESS Conference on Computers and Accessibility*. ASSETS '23. New York, NY, USA: Association for Computing Machinery, 2023. DOI: 10.1145/3597638.3608426. URL: https://doi.org/10.1145/3597638.3608426.

[312] Zheshen Wang, Baoxin Li, Terri Hedgpeth, and Teresa Haven. "Instant tactile-audio map: enabling access to digital maps for people with visual impairment". In: *Proceedings of the 11th International ACM SIGACCESS Conference on Computers and Accessibility*. Assets '09. Pittsburgh, Pennsylvania, USA: Association for Computing Machinery, 2009, pp. 43–50. ISBN: 9781605585581. DOI: 10.1145/1639642.1639652. URL: https://doi.org/10.1145/1639642.1639652.

[313] T. Watanabe, M. Kobayashi, Shun Ono, and K Yokoyama. "Practical use of interactive tactile graphic display system at a school for the blind (2)". In: *ICTE2006*. Nov. 2006. URL: http://vips.eng.niigata-u.ac.jp/Tactile/TactileDrawingSystem/m-ICTE_TactileGraphics.pdf.

[314] Tetsuya Watanabe and Makoto Kobayashi. "A Prototype of the Freely Rewritable Tactile Drawing System for Persons who are Blind". In: *Journal of Visual Impairment & Blindness* 96.6 (2002), pp. 460–464. DOI: 10.1177/0145482X0209600611. eprint: https://doi.org/10.1177/0145482X0209600611. URL: https://doi.org/10.1177/0145482X0209600611.

[315] Tetsuya Watanabe and Makoto Kobayashi. "An interactive tactile display for blind children — Evaluation at a school for the blind —". In: *The 23rd Asia-Pacific International Seminar on Special Education* (Oct. 2003), pp. 45–48. URL: https://www.researchgate.net/publication/281506005_An_Interactive_Tactile_Display_for_Blind_Children.

[316] Gerhard Weber. "ICCHP Keynote: Designing Haptic Interaction for a Collaborative World". In: *Computers Helping People with Special Needs*. Ed. by Klaus Miesenberger, Joachim Klaus, Wolfgang Zagler, and Arthur Karshmer. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010, pp. 431–438. ISBN: 978-3-642-14100-3. URL: https://doi.org/10.1007/978-3-642-14100-3_64.

[317] Gerhard Weber. "Interaktive Dialogtechniken für blinde Rechenbenutzer". PhD thesis. Universität Stuttgart, 1989.

[318] Roel J. Wieringa. "What Is Design Science?" In: *Design Science Methodology for Information Systems and Software Engineering*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2014, pp. 3–11. ISBN: 978-3-662-43839-8. DOI: 10.1007/978-3-662-43839-8_1. URL: https://doi.org/10.1007/978-3-662-43839-8_1.

[319] Roelf J. Wieringa. *Design science methodology for information systems and software engineering*. Undefined. 10.1007/978-3-662-43839-8. Netherlands: Springer, 2014. ISBN: 978-3-662-43838-1. DOI: 10.1007/978-3-662-43839-8. URL: https://doi.org/10.1007/978-3-662-43839-8.

[320] Robert F Woolson. "Wilcoxon signed-rank test". In: *Encyclopedia of Biostatistics* 8 (2005). DOI: https://doi.org/10.1002/0470011815.b2a15177. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/0470011815.b2a15177.

[321] Tatsuya Yamaji. *This time, a "writeable" braille display (BinWord)*. From the exhibition at the International Home Care and Rehabilitation Exhibition 2005 (HCR2005). Published on September 30th, 2005. 2005. URL: http://www.binword.com/blog/archives/000436.html.

[322] Jiao Yang, Gong Jiangtao, and Xu Yingqing. "Graille: Design Research of Graphical Tactile Display for the Visually Impaired". In: *Practice* (2016), pp. 94–96. URL: http://www.adi.tsinghua.edu.cn/upload_files/atta/1547797093034_31.pdf.

[323] Jiao Yang and Xu Yingqing. "Accessible design research: A graphical tactile display for the visually impaired". In: *Science & Technology Review* 41.8, 65 (2023), p. 65. DOI: 10.3981/j.issn.1000-7857.2023.08.006. URL: http://www.kjdb.org/EN/10.3981/j.issn.1000-7857.2023.08.006.

[324] Wenzhen Yang, Jinpen Huang, Ruirui Wang, Wen Zhang, Haitao Liu, and Jianliang Xiao. "A Survey on Tactile Displays For Visually Impaired People". In: *IEEE Transactions on Haptics* 14.4 (2021), pp. 712–721. DOI: 10.1109/TOH.2021.3085915. URL: https://doi.org/10.1109/TOH.2021.3085915.

[325] Juan Jose Zarate, Olexandr Gudozhnik, Anthony Sébastien Ruch, and Herbert Shea. "Keep in Touch: Portable Haptic Display with 192 High Speed Taxels". In: *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. CHI EA '17. Denver, Colorado, USA: Association for Computing Machinery, 2017, pp. 349–352. ISBN: 9781450346566. DOI: 10.1145/3027063.3052957. URL: https://doi.org/10.1145/3027063.3052957.

[326] Juan José Zárate and Herbert Shea. "Using Pot-Magnets to Enable Stable and Scalable Electromagnetic Tactile Displays". In: *IEEE Transactions on Haptics* 10.1 (2017), pp. 106–112. DOI: 10.1109/TOH.2016.2591951. URL: https://doi.org/10.1109/TOH.2016.2591951.

[327] Limin Zeng. "Non-Visual 2D Representation of Obstacles". In: *SIGACCESS Access. Comput.* 102 (Jan. 2012), pp. 49–54. ISSN: 1558-2337. DOI: 10.1145/2140446.2140457. URL: https://doi.org/10.1145/2140446.2140457.

[328] Limin Zeng, Mei Miao, and Gerhard Weber. "Interactive Audio-haptic Map Explorer on a Tactile Display". In: *Interacting with Computers* 27.4 (Feb. 2014), pp. 413–429. ISSN: 0953-5438. DOI: 10.1093/iwc/iwu006. eprint: https://academic.oup.com/iwc/article-pdf/27/4/413/9644221/iwu006.pdf. URL: https://doi.org/10.1093/iwc/iwu006.

[329] Limin Zeng, Denise Prescher, and Gerhard Weber. "Exploration and Avoidance of Surrounding Obstacles for the Visually Impaired". In: *Proceedings of the 14th International ACM SIGACCESS Conference on Computers and Accessibility*. ASSETS '12. Boulder, Colorado, USA: Association for Computing Machinery, 2012, pp. 111–118. ISBN: 9781450313216. DOI: 10.1145/2384916.2384936. URL: https://doi.org/10.1145/2384916.2384936.

[330] Limin Zeng and Gerhard Weber. "3DOD: A haptic 3D Obstacle Detector for the Blind". In: *Mensch & Computer 2012 – Workshopband: interaktiv informiert – allgegenwärtig und allumfassend!?* München: Oldenbourg Verlag, 2012, pp. 485–488. ISBN: 978-3-486-71990-1. URL: https://dl.gi.de/items/bc672edd-7494-4e17-b2ba-72d985445a80.

[331] Limin Zeng and Gerhard Weber. "ATMap: Annotated Tactile Maps for the Visually Impaired". In: *Cognitive Behavioural Systems*. Ed. by Anna Esposito, Antonietta M. Esposito, Alessandro Vinciarelli, Rüdiger Hoffmann, and Vincent C. Müller. Berlin, Heidelberg: Springer Berlin Heidelberg, 2012, pp. 290–298. ISBN: 978-3-642-34584-5.

[332] Limin Zeng and Gerhard Weber. "Audio-Haptic Browser for a Geographical Information System". In: *Computers Helping People with Special Needs*. July 2010, pp. 466–473. ISBN: 978-3-642-14099-0. DOI: https://doi.org/10.1007/978-3-642-14100-3_70. URL: https://doi.org/10.1007/978-3-642-14100-3_70.

[333] Limin Zeng and Gerhard Weber. "Exploration of Location-Aware You-Are-Here Maps on a Pin-Matrix Display". In: *IEEE Transactions on Human-Machine Systems* 46.1 (2016), pp. 88–100. DOI: 10.1109/THMS.2015.2477999. URL: https://doi.org/10.1109/THMS.2015.2477999.

[334] Limin Zeng, Gerhard Weber, and Ulrich Baumann. "Audio-haptic you-are-here maps on a mobile touch-enabled pin-matrix display". In: *2012 IEEE International Workshop on Haptic Audio Visual Environments and Games (HAVE 2012) Proceedings*. 2012, pp. 95–100. DOI: 10.1109/HAVE.2012.6374428. URL: https://doi.org/10.1109/HAVE.2012.6374428.

[335] Limin Zeng, Gerhard Weber, Ingo Zoller, Peter Lotz, Thorsten A. Kern, Jörg Reisinger, Thorsten Meiss, Thomas Opitz, Tim Rossner, and Nataliya Stefanova. "Examples of Haptic System Development". In: *Engineering Haptic Devices: A Beginner's Guide*. London: Springer London, 2014, pp. 525–554. ISBN: 978-1-4471-6518-7. DOI: 10.1007/978-1-4471-6518-7_14. URL: https://doi.org/10.1007/978-1-4471-6518-7_14.

[336] Zhuohao Zhang, John R Thompson, Aditi Shah, Manish Agrawal, Alper Sarikaya, Jacob O. Wobbrock, Edward Cutrell, and Bongshin Lee. "ChartA11y: Designing Accessible Touch Experiences of Visualizations with Blind Smartphone Users". In: *Proceedings of the 26th International ACM SIGACCESS Conference on Computers and Accessibility*. ASSETS '24. St. John's, NL, Canada: Association for Computing Machinery, 2024. DOI: 10.1145/3663548.3675611. URL: https://doi.org/10.1145/3663548.3675611.

APPENDIX

A. SUPPLEMENTARY DOCUMENTATION ON 2DRTP DISPLAYS

A.1. THE PROGRESSION ON 2DRTP DISPLAYS

This analysis delves into the evolution of 2D Refreshable Tactile Pin (2DRTP) displays, shedding light on the variations in hardware and software components, the range of devices developed, and the outcomes of these projects. The exploration encompasses a comprehensive view of the 2DRTP landscape within the scientific community and market field, encompassing from unrealised projects to finished market products.

HYPERBRAILLE

When providing an overview of 2DRTP devices, it is imperative to highlight the **HyperBraille** project. Widely recognised as the model of device development and user interface advancements, the HyperBraille project has played a pivotal role in shaping this field. The primary objective of this project was to enhance employment opportunities for individuals with visual impairments by providing modern graphical user interfaces. The main challenge was to convert and map the contents of graphical desktop applications to a tactile graphic representation using a pin-matrix display with a limited resolution of 120 × 60 pins. Collaboratively undertaken by the HyperBraille project and Metec AG [7], various pin-matrix devices incorporating the HyperBraille software [43] were developed. The most pertinent user interfaces and tactile displays derived from this project have been included in this dissertation for a comprehensive investigation.

The development of the "Stuttgarter Stiftplatte" in 1984/1985 [267] laid the foundation for the groundbreaking Dot Matrix Display **(DMD) 12060** [266], produced by Metec AG in 1989 [205] (figure A.1). The DMD marked the birth of state-of-the-art 2DRTP displays, revolutionising the field by integrating a large refreshable pin array surface, measuring 120 pins in width and 60 in height (7200 in total), along with audio feedback. The impact of the DMD 12060 was far-reaching, pioneering advancements across various domains such as orientation and mobility, education systems, support for Word and Excel sheets, graphics and 3d model rendering, interactive models, and entertainment. Notably, several studies [226, 174] have leveraged the DMD's capacities to further applications, including the representation of circuit diagrams, mathematical graphics [156], drawing systems [317], and even tactile rendering of web pages using a Mozilla Firefox Extension [254, 255, 253].

The DMD incorporates two finger sensors for each hand, utilising electrical coil mechanisms to achieve precise eight-dot positioning on the pin-matrix surface. These sensors enable direct text and graphics manipulation on the display and support for gesture navigation, including scrolling and page refreshing [317].

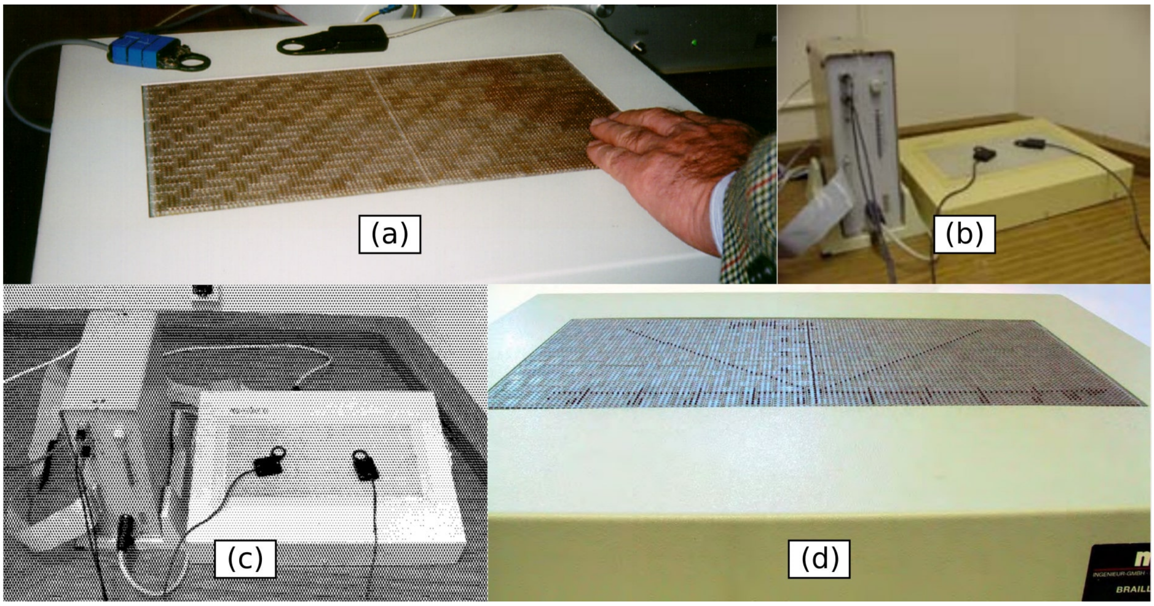

Figure A.1.: (a) The Stuttgarter Stiftplatte [174], (b), (c), and (d) the Dot Matrix Display (DMD) 12060 [130, 156, 255]

Following the introduction of the DMD 12060, Metec continued its development efforts and introduced the **BrailleDis 9000** in 2008 [308] (figure A.2). An important innovation of the UI features of this device is its division into four distinct regions on the refreshable pin-matrix surface [259, 288]. These regions include the header, body, structure, and detail regions. The header zone provides information about statuses and main properties, while the body region occupies approximately 58.0% of the display screen and presents the main application content. The structure zone, positioned on either the left or right side of the screen, is used to highlight the current position and enable similar operations. The detail region displays comprehensive details of focused elements.

The UI of the BrailleDis 9000 extends beyond tactile display capabilities by incorporating input gestures through touch sensors integrated into the braille cells [284]. These sensors enable the detection of finger and hand pressure points, facilitating a range of interactions and even supporting multi-touch input gesture recognition [261, 262], thereby further enhancing its usability. With a refreshment rate of 5Hz [45], the device supports dynamic feedback, such as blinking pins, which effectively indicate points of interest [332].

The BrailleDis 9000 has found applications in diverse domains, including entertainment (gaming) [130], graphics representation involving colour coding [289, 288], and orientation and mobility aids, such as a GIS map viewer [332]. Additionally, it enables more advanced user interface interactions, including multi-view windowing techniques and other window operations [290, 288, 232], drag and drop interaction [277].

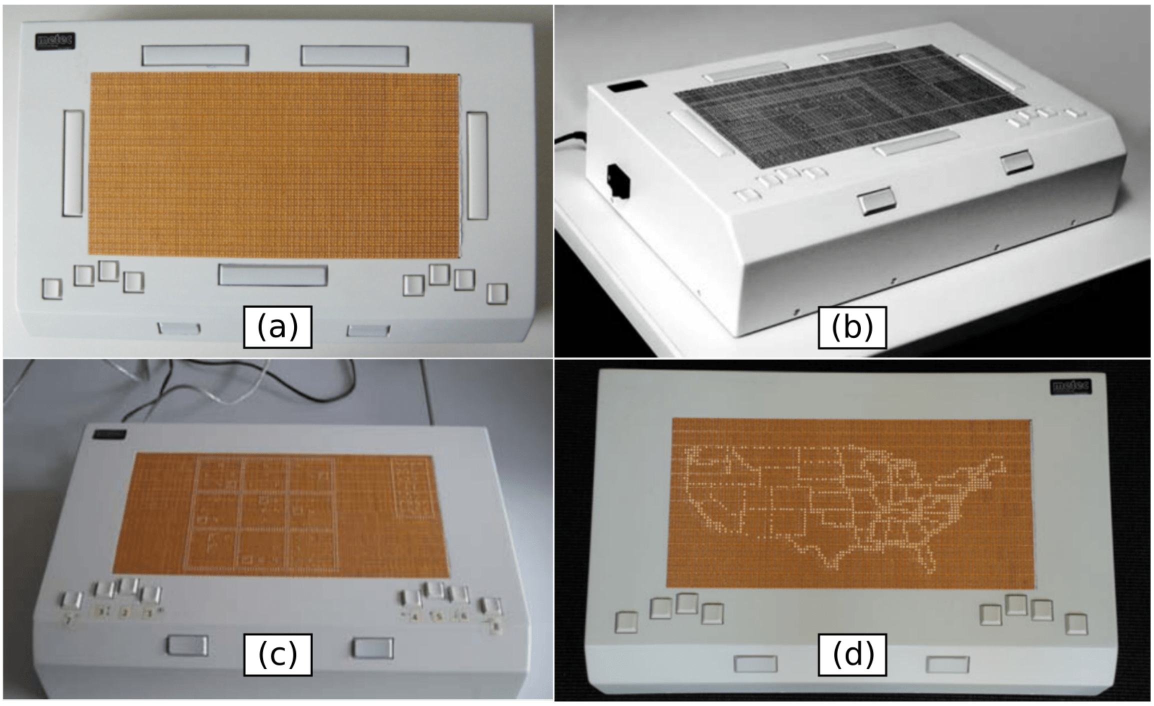

Figure A.2.: The BrailleDis 9000 device (by Metec AG). (a) Empty pin-matrix surface [259]. (b) Multi-view windowing feature [232]. (c) Entertainment domain [130]. (d) Map GIS viewer [332].

In 2012, Metec AG developed the **Mobile HyperBraille Display** (figure A.3), a portable and smaller refreshable tactile pin-matrix device. Different from its predecessors, this device was specifically designed to be carried along and serves as a tactile user interface for 3D obstacle detection and the tactile representation of GIS maps [330, 334]. It caters to the domain of orientation and mobility aids, providing invaluable assistance to the visually impaired community. The Mobile HyperBraille Display features a 32×30 pin array, smaller than other HyperBraille models. It is used with additional components, including a Wii remote controller equipped with buttons for seamless panning and zooming operations, a smartphone with a digital compass and GPS, and a lightweight laptop for running the main program [335, 333].

The device's versatility has led to a wide array of applications and has played an integral role in several studies that have significantly advanced the technology field. Noteworthy investigations include research on discriminating small, context-independent tactile symbols of sizes 3x3 and 4x4 [184], exploring the potential of 2DRTP devices to enhance spatial working memory and performance in spatial tasks with straightforward geometrical dispositions [187, 185], and developing audio-tactile You-are-here maps to facilitate exploration of surrounding environments and locate nearby points of interest [333].

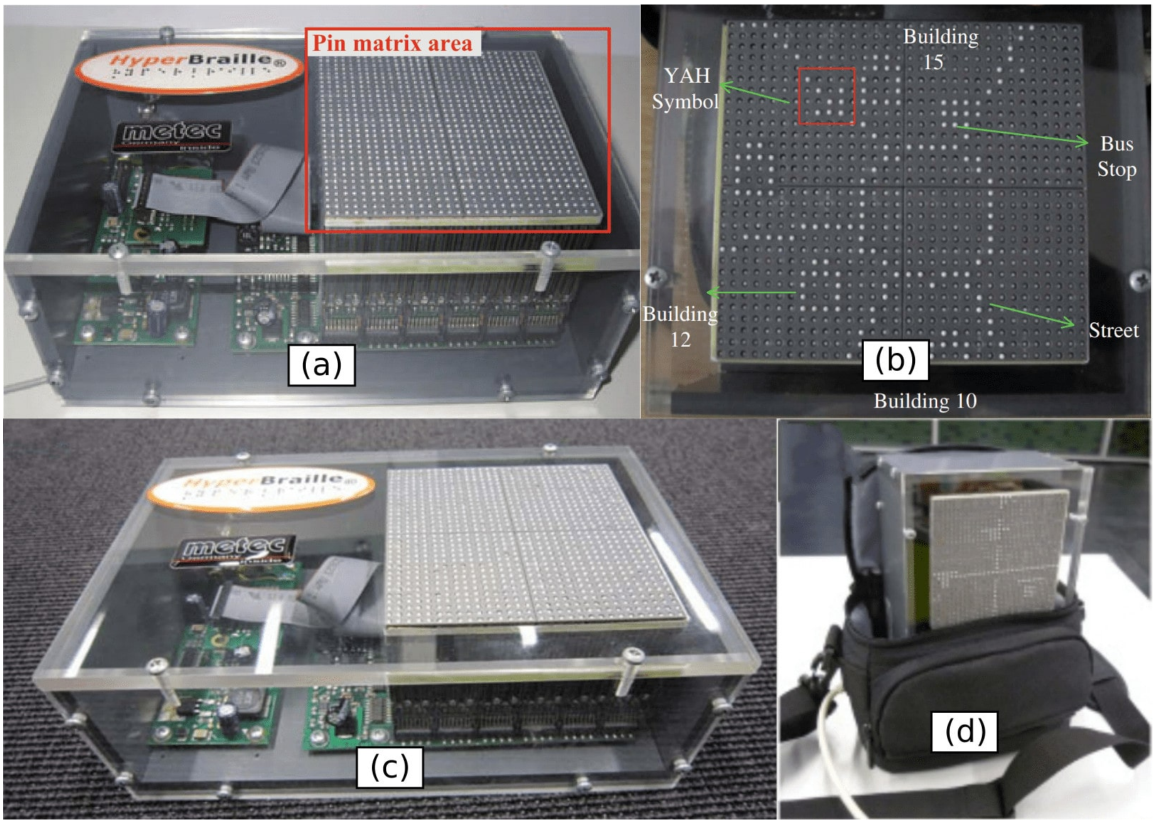

Figure A.3.: The Mobile HyperBraille Display (by Metec AG). (a) and (c) Empty pin-matrix surface [334, 335]. (b) GIS Map representation [334]. (d) Obstacle detection information [330].

Metec AG introduced the **BrailleDis 7200** (see Figure A.4), an upgraded version of the previous display presenting new features and functionalities in 2014 [42]. Notable enhancements encompass input controls, keyboard positioning, and input functionalities. The addition of mouse wheels, cursor keys, gesture keys, and a navigation bar enabled independent operation without the need for an external keyboard. This redesign aimed to improve the user experience and interaction [227]. The new version also improves on the BrailleDis 9000 with a higher display refresh rate of 20 Hz (previously 5 Hz), allowing smoother and more effective display of dynamic content.

In mobility and orientation, the BrailleDis 7200 has been used for a Map-Explorer UI founded on OpenStreetMap data [328, 148], and for an obstacle detection UI that represents 2D/3D obstacles on its pin-matrix surface [327]."

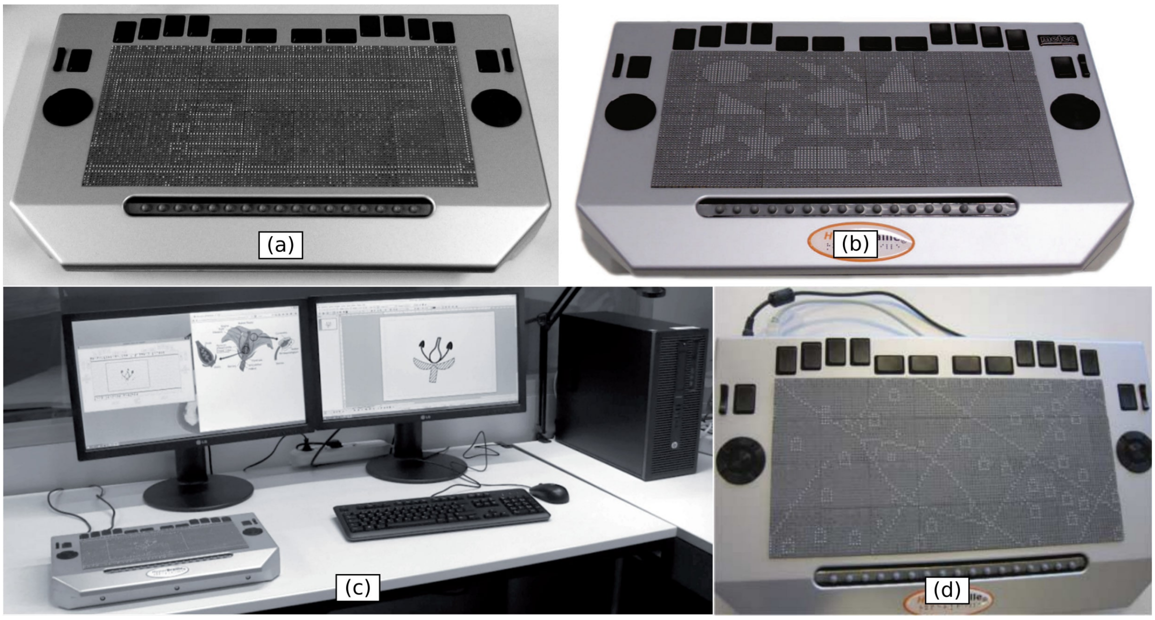

Figure A.4.: BrailleDis 7200 (by Metec AG). (a) Pin-matrix surface with window separation view [42]. (b) Libre Office graphic doc representation [230]. (c) The Tangram workstation [51]. (d) Map-explorer UI [328].

J. Bornschein et al. introduced the Tangram workstation to support graphic editing via Libre and OpenOffice Draw [50, 51], and developed BrailleIO, a framework for consistent 2D tactile UI development [46, 47]. In education, the BrailleDis 7200 enabled tasks like filling PDF forms and interacting with GUI elements by users with BVI [173, 43]. They also integrated advanced UI components, such as focus zoom, ensuring focused elements remain within the tactile area after zooming [230]. The device introduced multiple tactile views (symbol, layout, outline) to support different tasks and contexts [231, 227], advancing the accessibility of 2D data on 2DRTP devices [43].

In 2016, Metec AG made significant advancements to the BrailleDis series by introducing the **BrailleDis 6240**, also known as Hyperbraille S or Hyperbraille F [6]. This new iteration featured a smaller tactile surface with 104 x 60 taxels (6240 in total), setting it apart from its predecessor. The BrailleDis 6240 was complemented by a drawing workstation (based on LibreOffice Draw software [107]), offering a cohesive experience when combined with a wireless digitiser stylus [48, 49]. With this setup, a traceable line of pins appeared underneath the pen tip while drawing, allowing blind users to perceive the images they create immediately. This innovative workstation empowered individuals with visual impairments not only to manipulate existing graphics but also to draw new images independently using standard shapes like rectangles, triangles, and circles, accessible through shape palettes in a menu.

The BrailleDis 6240 found applications in various domains, including Education, where it proved valuable in representing graphical elements and text information on PDF STEM documents [203] and in representing mathematical data plots to understand mathematical functions better [265]. Notably, studies demonstrated that the interaction techniques presented in this two-dimensional tactile display significantly improved the accessibility of complex graphics in STEM fields at the university level for students with visual impairments. These developments have paved the way for fostering inclusivity and enhancing educational opportunities for individuals with blindness. Currently, the BrailleDis 6240 is the latest iteration in the BrailleDis and Hyperbraille line, and it is accessible for acquisition through Metec AG [6].

Figure A.5.: The BrailleDis 6240 (by Metec AG). (a) Pin-matrix surface with Metec icon [6]. (b) Mathematical data plots representation [265]. (c) Graphics interaction [49]. (d) Drawing workstation with wireless digitiser stylus [48].

Regarding the range of refreshable tactile pin-matrix devices offered by Metec AG, besides the BrailleDis 6240, two other 2DRTP displays are currently available: the Hyperflat [8] and the most recent addition, the Tactile2D [9]. These devices showcase Metec AG's commitment to advancing the field of tactile graphics, providing users with a versatile selection of devices.

The **Hyperflat** is a 2DRTP display designed to be linked with tablets or smartphones [8]. Incorporating the identical piezo-driven dots pin mechanism as the BrailleDis 6240, it achieves a refresh rate of 20 Hz. The device features a more compact pin-matrix surface, housing 76 x 48 pins (3648 pins). Its applications span diverse domains, from representing mathematical line charts sourced from GeoGebra software [8] to visualising indoor floor plans and exploring room shapes [125, 104].

More recently, in 2020, Metec AG launched the **Tactile2D**, the company's first independent 2DRTP display with a smaller pin-matrix of 48 x 39 pins [9]. The company's primary goal with this iteration was to create a more portable device that users could conveniently carry as a shoulder bag. However, due to its reduced size, the amount of information the device can represent is limited. Consequently, relatively few scientific contributions and investigations have been conducted with this device.

Figure A.6.: The Tactile2D and Hyperflat 2DRTP Displays from Metec AG. (a) Tactile2D with split window [9]. (b) Tactile 2D being used with a shoulder strap [45]. (c) Hyperflat representing mathematical line charts [8]. (d) Hyperflat representing floor plans [125].

GWP

In 2001, Handy Tech Elektronik GmbH (now known as Help Tech GmbH) introduced the **Graphic Window Professional** (GWP) [115] (figure A.7). This compact refreshable tactile pin-matrix display features a 24 x 16 pin array (384 pins), supporting panning and zooming interactions on tactile images through cursor keys. Despite its small size, the device implements image-processing techniques to extract and display essential details of tactile graphics on the pin-matrix surface [69]. However, it should be noted that the GWP's pin spacing of 3mm is not compliant with the Braille standards [53, 300], leading to challenges when rendering more intricate curved lines [216].

The GWP demonstrated remarkable versatility by enabling blind students to independently explore mathematical graphics when integrated with the math program Maple, giving rise to the Mapple GWP system [17]. Within this system, blinking pins served as markers, assisting BVI students in navigating the tactile surface with precision. Blinking pins indicate a responsive refreshment rate, likely operating at 1 Hz or higher. Nevertheless, due to the GWP's age and discontinuation, obtaining further information about the device, such as its refresh rate, is no longer possible. Notably, the Mapple GWP system allowed users to select specific objects, providing the freedom to explore individual diagrams or multiple ones displayed simultaneously in the same window [28].

Figure A.7.: The GWP (Graphic Window Professional) device from Help Tech GmbH [115, 17].

DOT VIEW

The ’Dot View’ series by KGS Corporation [74] played a key role in the early development of 2DRTP displays. Similar to the HyperBraille and Metec devices, it employed piezoelectric pin technology. Since 2002, KGS has developed devices that helped shape early 2DRTP prototypes and advance dynamic tactile graphics technology.

Introduced in 2002, the **Dot View DV-1** by KGS Corporation featured 768 pins (32×24), arrow keys, buttons, and a 4-way lever, supporting both computer operation and tactile figure learning [79] (Figure A.8). With a 20Hz refresh rate and 3mm pin spacing, it matched devices like the BrailleDis 7200 and DMD 12060. While scientific studies are limited, some explored its use in displaying handwritten curves and assessing BVI users’ ability to recognise graphical properties in educational contexts [109]. The Dot View DV-1 laid the groundwork for systems like **MIMIZU** (2002), which paired the device with a stylus on a two-axis arm to enable precise drawing near the tactile surface [170, 314]. Designed to support BVI students in shape and figure creation with real-time tactile feedback and line erasure, its effectiveness was demonstrated in school settings [315]. Later enhancements included a 3d digitiser for capturing stylus tip positions, allowing students to reproduce 2D drawings after exploring 3d sculptures [313]. To reduce cost and complexity, the 3d digitiser was later replaced by an ultrasonic pen [109].

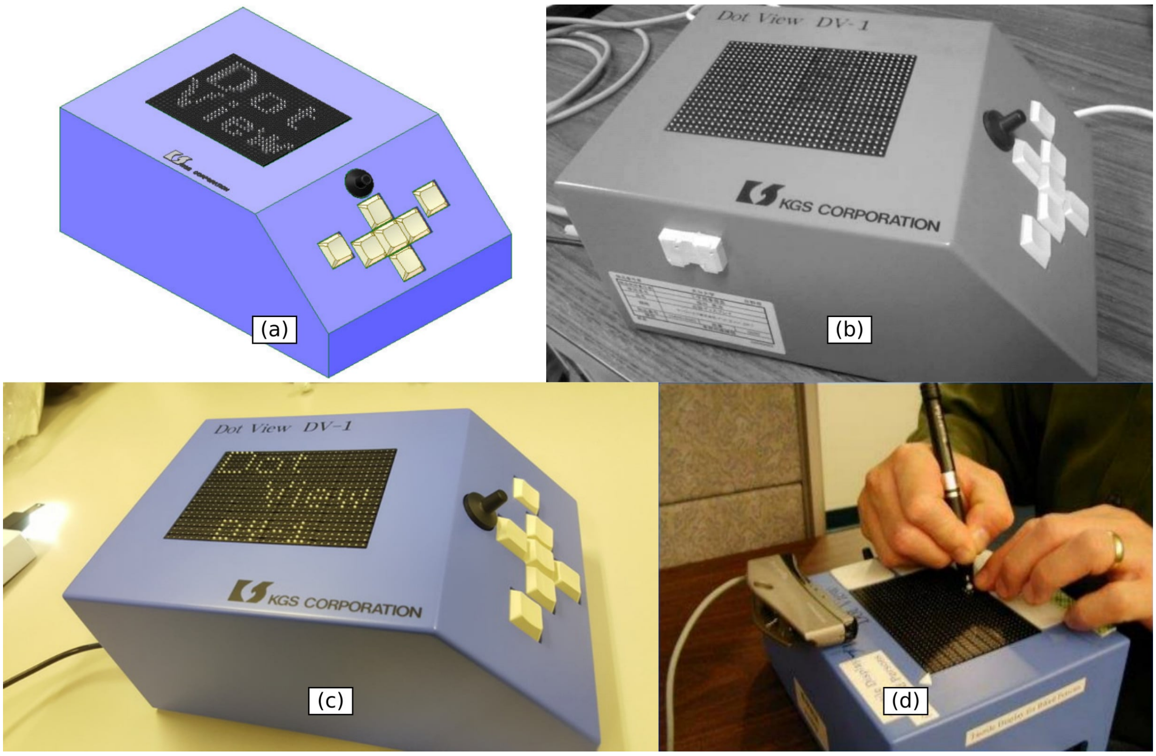

Figure A.8.: The Dot View DV-1 from KGS Corporation. (a) Dot View 3d object representation [79]. (b) empty pin-matrix surface [109]. (c) [45]. (d) The MIMIZU system with Dot View DV-1 [313].

In 2003, KGS Corporation introduced the next iteration of the "Dot View" series, known as the **Dot View DV-2** [80] (figure A.9). Notably, the Dot View DV-2 boasted several improvements over its predecessor, the Dot View DV-1. It featured a larger tactile area, accommodating 1536 pins (48 x 32), and exhibited a lighter weight of 1.5 kg. Another significant enhancement was the reduced pin-spacing of 2.4mm, offering improved precision and better compatibility with Braille dimensions norms [53].

Building upon its predecessor, the Dot View DV-2 also played a significant role in developing and implementing the **MIMIZU** mechanical system [171]. This system version utilised an ultrasonic stylus pen, enabling blind users to create drawings with an erasing function directly on the tactile surface. The MIMIZU system served not only as a tool for drawing but also as a communication platform, allowing blind individuals to exchange tactile image information with one another. Furthermore, the system demonstrated versatility by delivering interactive entertainment interfaces, including a ping-pong-like game with a 2x2 pin-square ball and stylus pen racket [172], as well as a bird's-eye-view layout representation of football matches with real-time tactile feedback for players and the ball [217].

Additionally, the Dot View DV-2 was pivotal in advancing the development and practicality of refreshable tactile pin-matrix displays, profoundly impacting various domains. One notable application was the Drawing Assistance system, where the pin-matrix surface effectively showcased graphics and figures that blind and visually impaired users designed on their computers [287]. The scientific community also explored the potential of drawing software, enabling users to manipulate geometric shapes, such as placing squares on the pin-matrix and examining Excel graphs [169]. Furthermore, the authors in [272] integrated the Dot View DV-2 with a six-axis touch/force sensor securely affixed to the device's solid plate. This tactile graphic system empowered BVI users to interact with floor plans of buildings and seamlessly perform touch, click, scroll, and zoom operations, fostering a more immersive experience.

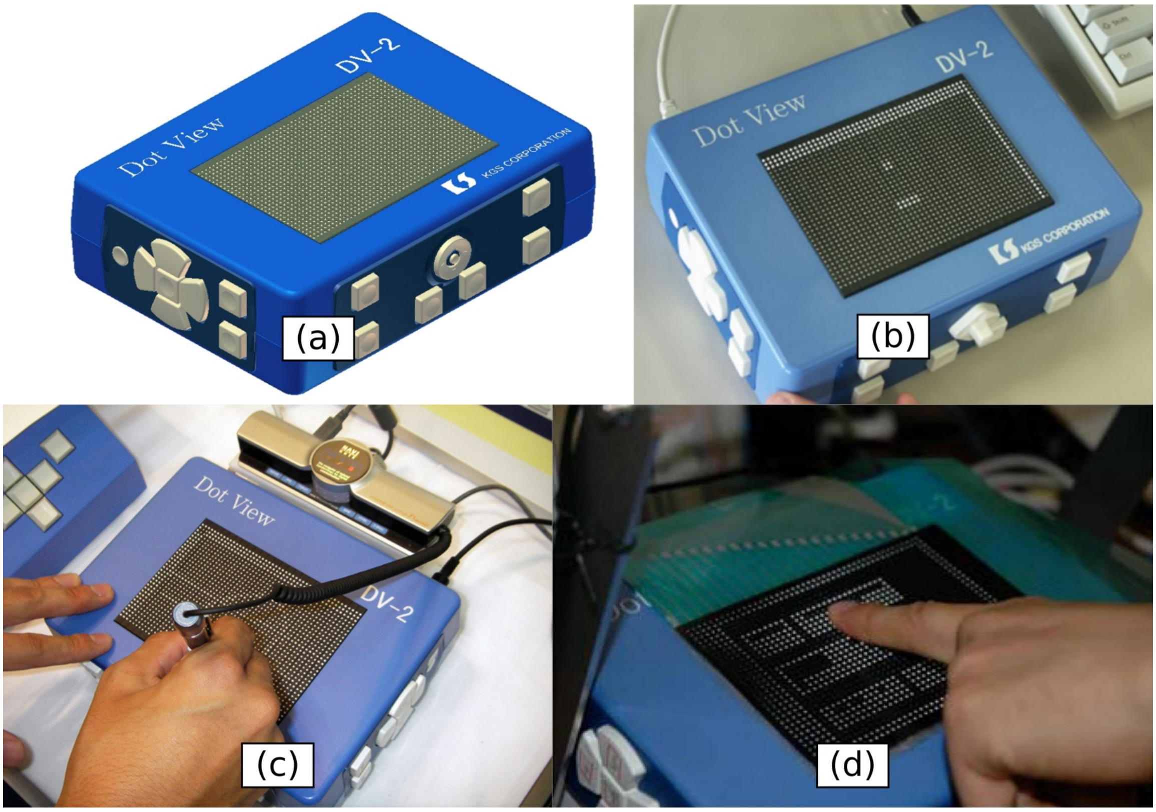

Figure A.9.: The Dot View DV-2 from KGS Corporation. (a) Dove View 3d object representation [80]. (b) Manipulation of geometric objects (squares) [169]. (c) The MIMIZU system with Dot View DV-2 [321] (d) Dot View DV-2 combined with touch panel [166].

Beyond focusing on the assistive technology domain, some projects used the Dot View DV-2 in applications for sighted people. The authors in [166] synchronised the tactile feedback of the Dot View DV-2 with a visual screen image for the context of a car navigation system. The authors fixed a thin touch panel on the Dot View DV-2 to allow touch interactions. This is a very interesting point since we can see that the development of refreshable tactile pin-matrix displays not only benefits the world of BVI people but also presents innovative opportunities for sighted users to enhance their experiences.

NIST

In 2002 [278], the National Institute of Standards and Technology initiated the development of a refreshable tactile pin-matrix display, which later became known as the **NIST refreshable tactile graphic display** [249] (figure A.10). This device features a pin matrix with 71 x 51 pins (3621 in total) mounted on an X-Y graphics plotter, each equidistant from the others with a pin spacing of 2.54mm. Notably, the NIST display sought to reduce costs by adopting a more affordable technology, departing from the traditional one actuator per pin approach [251]. Instead, it utilises a design with simple metal pins devoid of powered components, employing a single device to control all pins via a locking mechanism [250]. While this cost-effective design offers benefits, it results in a lower dynamic performance compared to traditional approaches seen in devices like the Hyperbraille series [308, 42], limiting its refresh rate to 0.03 Hz (on average, depending on the image complexity).

Despite its cost-effectiveness and unique pin control mechanism, the NIST device did not receive as much attention regarding contributions and studies on its various potential applications, unlike other well-established devices like the HyperBraille and Dot View series. Nevertheless, the device found applications in various domains, including education systems, engineering design, web surfing, and image viewing, showcasing its versatility and potential impact across different fields.

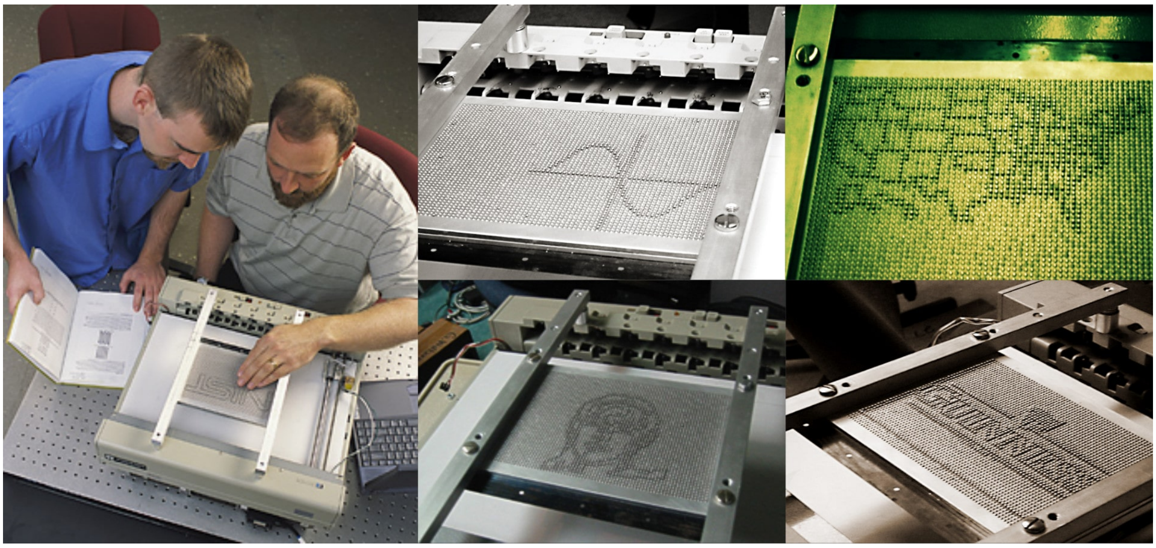

Figure A.10.: The NIST refreshable tactile graphic display. [251]

ITACTI

The ITACTI project (Interactive Tactile Interface for the Visually Impaired), completed in 2005, successfully developed a cutting-edge tactile display prototype featuring a 128x64 pin matrix, totalling 8192 pins, referred to as the **ITACTI** device [189]. In line with many 2DRTP display projects, the primary focus was hardware development. The ITACTI display employed actuator arrays utilising electrorheological fluid (ERF) to raise and lower pins by varying the pressure within the ERF. The final prototype achieved a pin-matrix refresh rate of 7 seconds and incorporated interactive touch sensor feedback at the individual Braille cell level (2x4 pins) [301, 303, 302]. While aiming to lower 2DRTP display costs, traditional ERFs with micro-particles can adversely affect performance, resulting in inaccurate pin-matrix representations [150].

Furthermore, the ITACTI research delved into user interface and software aspects. The device demonstrated its capability to represent various simple shapes, objects, text, and figures by using the TAWIS (Tactile Windows screen reader) software. This software, developed by Friedrich Luthi from Metec AG, was also employed by the HyperBraille displays [316]. However, it's worth noting that while ITACTI showcased its compatibility with the software, its primary use remained associated with HyperBraille devices. Regrettably, no additional information regarding project outcomes is available, and the project has likely concluded.

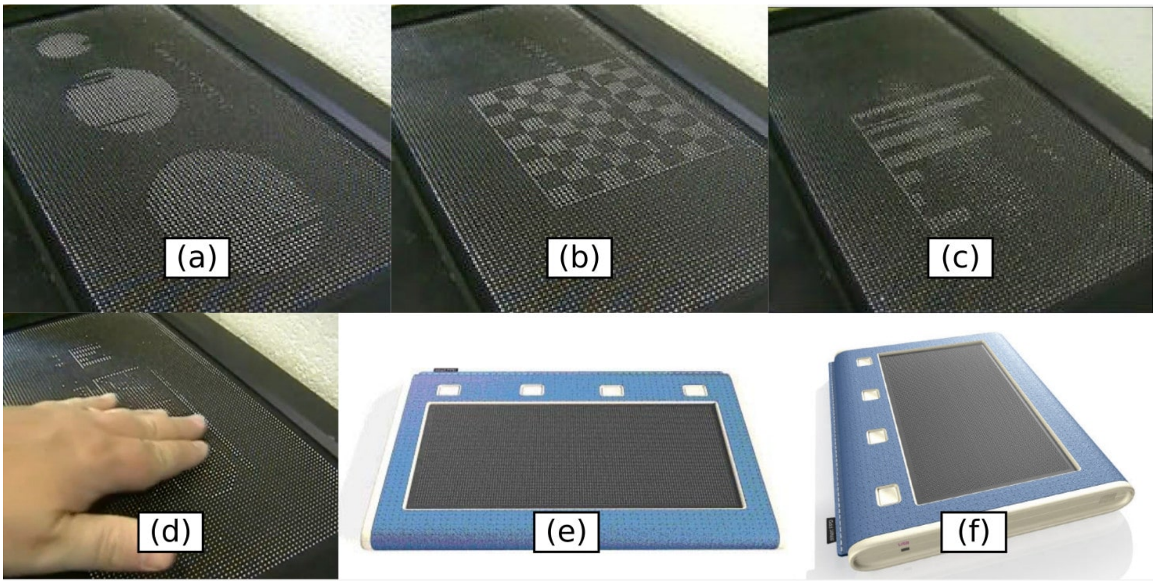

Figure A.11.: (a,b,c,d) The ITACTI display [189, 301, 303]. (e,f) Proposed mock-up enclosure for the final prototype. [301]

OUV3000

In 2006, Uniplan Co. released the **OUV3000**, a tactile display featuring 3072 pins (64 x 48) arranged at 2.8 mm intervals [70] (figure A.12). The OUV3000 utilised a single row of solenoids for its pin mechanism, distinguishing it from contemporaneous devices like the Dot View series [169]. Notably, the OUV3000 featured a manual erasing method with a refresh rate of 22 seconds. Unfortunately, due to language barriers, limited available information, and project discontinuation, comprehensive details regarding its user interface and application domains remain elusive.

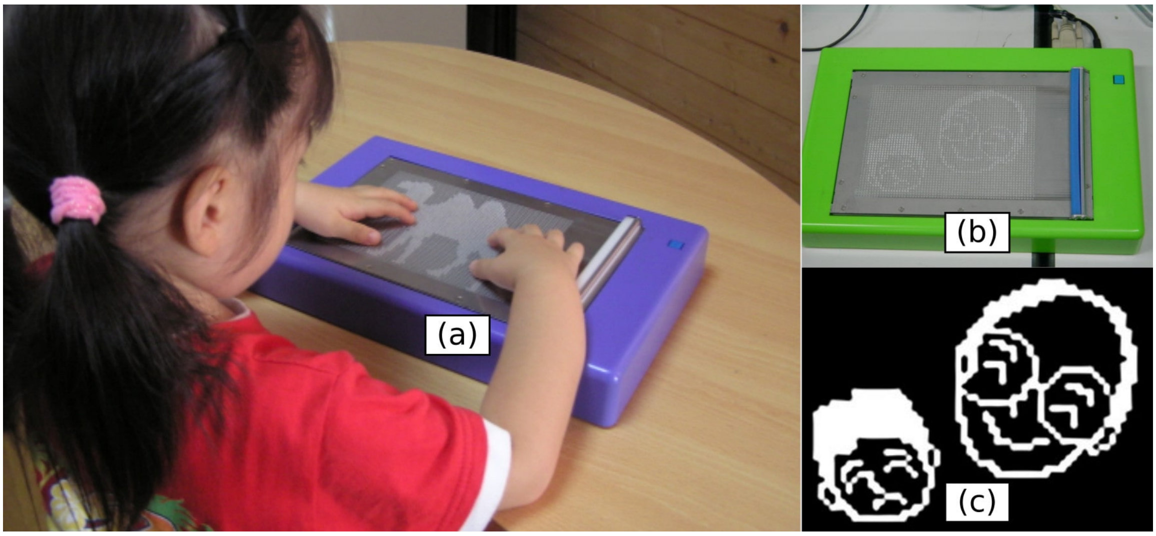

Figure A.12.: The tactile display OUV3000 from Uniplan Co. (a,b). 64x48 binary image representation (c). [70]

SHIMADA

Shimada et al. integrated eight 32x12 pin-matrix modules from KGS Corporation with a 2.4mm pin-spacing to construct Shimada's 2DRTP in 2010 [270] (figure A.13). In addition to the tactile surface, this device incorporated a Force-based position estimation sensor, enabling click, scroll and zoom operations. Notably, the full-page refresh rate of the device was only 50ms. The author highlights the significance of the tactile surface size, emphasising that larger surfaces are preferable as they facilitate natural bi-manual reading, a technique commonly employed by individuals with BVI when exploring tactile graphics. Hence, the Shimada device featured eight 32x12 pin-matrix modules, a significant upgrade from its initial prototypes with only four [271].

While this project did not result in a commercial device, it played a significant role in user interface development, addressing various interface challenges. Motivated by the need to represent computer screens on 2DRTP devices, which typically have limited resolution, the authors focused on implementing scroll and panning techniques to enable the exploration of the entire PC screen on the tactile surface. Shimada et al. proposed using motor-driven tactile scroll bars to indicate the X and Y position of the PC's projected area [270].

Shimada's device included a tactile map application that combined tactile representations of colouring maps with audio explanations [272, 271, 270]. Users accessed information by clicking on the corresponding tactile element, triggering MP3 audio playback. However, despite the promising features of the Shimada device and tactile map application, the project ultimately ceased development after 2010, primarily due to the high cost associated with the device technology.

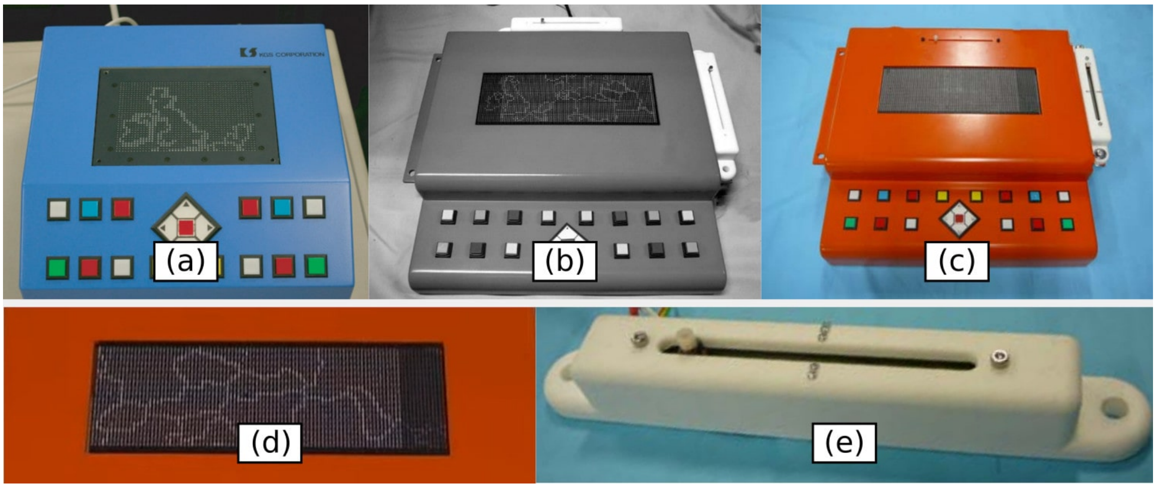

Figure A.13.: The Shimada's 2DRTP. The 48x32 prototype in 2008-2009 (a) [272, 271]. The 96x32 prototype in 2010 (b,c,d) with the motor-driven tactile scroll bar (e) [270, 179].

TACTIS

In 2015, Tactisplay Corp presented several conceptual refreshable tactile pin-matrix devices (Figure A.14). Although designed for specific applications, these devices never reached commercial production. Publicly available information is limited to technical reports and company data, with language barriers further restricting access to details or prototypes. Nonetheless, these concepts offer valuable insights for designing 2DRTP displays.

The **TACTIS 100** by Tactisplay Corp is a refreshable tactile multi-line display featuring four rows of 25 braille cells (100 total) [76]. It includes navigation buttons and tactile guidelines for intuitive use. Using only two actuator bars, the device refreshes at a slow rate of 0.2 Hz (5 seconds). Due to its non-uniform pin spacing, it is not suitable for 2D graphics but operates well for displaying structured text, equations, and simple tables.

The **TACTIS Table** by Tactisplay Corp, introduced in 2015, features a 120×100 grid of equidistant pins (12,000 total), with 2.5 mm spacing and 1.2 mm diameter [77]. Using two actuator bars, it refreshes in 8 seconds (0.125 Hz). Designed for educational use, it supports the tactile display of math, tables, graphs, and images, and includes zoom and panning for interactive exploration.

The **TACTIS Walk** by Tactisplay Corp features a 60×40 grid (2,400 pins) and maps USB camera input onto its tactile surface via binary image processing [78]. Using two actuator bars, it refreshes every 8 seconds (0.125 Hz). Designed for on-site use while walking, it supports obstacle and detail detection. No further research on this or the other Tactisplay Corp devices has been reported.

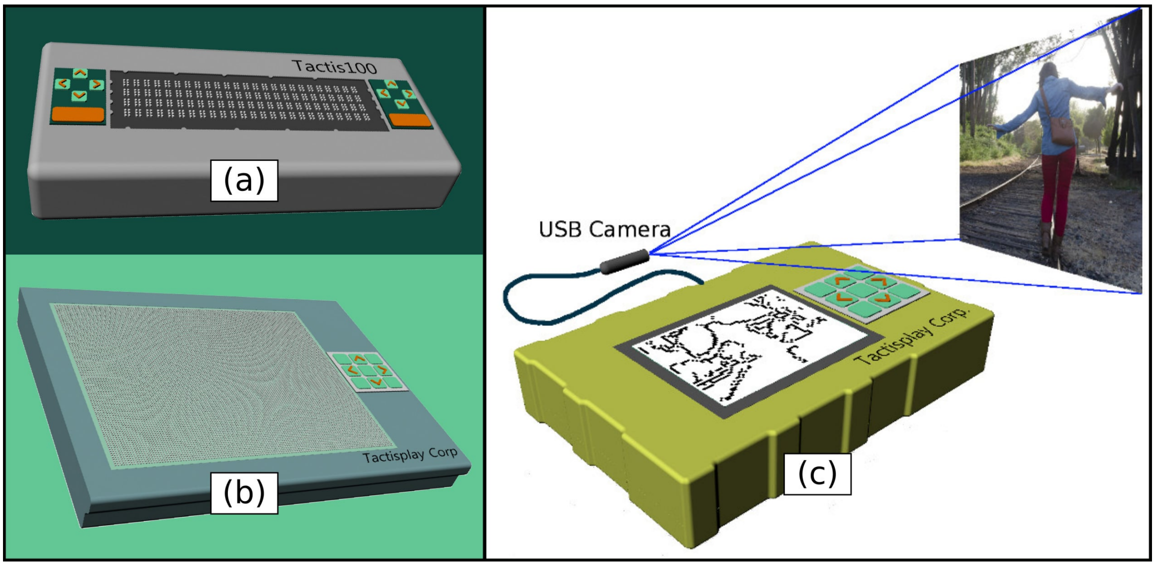

Figure A.14.: The TACTIS pin-matrix displays series from Tactisplay Corp. (a) TACTIS 100 [76], (b) TACTIS Table [77], and (c) TACTIS Walk [78].

GRAILLE

Since 2016, Tsinghua University in China has been developing the **Graille** Display [322] (figure A.15), a 2DRTP display with a total of 120 × 60 pins, equivalent in size to the BrailleDis9000 [308] and BrailleDis7200 [42]. It utilises a movable push-pull electromagnet for pin control and has voice output capabilities. Despite a slow 30-second refreshment rate [322], the pin-matrix updates sequentially from top to bottom, allowing users to engage with the content as it refreshes. A distinctive feature of the Graille Display is the presence of an auxiliary tactile guide slider (ring) located 10 mm above the Braille matrix [323]. This slider is designed to guide the user's finger to specific locations, but it can only accommodate a single finger, restricting multi-finger exploration and tactile context for blind users.

Having evolved into a physical prototype, Graille underwent rigorous testing to assess its practicality and efficacy. It was employed to represent mathematics graphics for visually impaired students in educational settings, yielding positive outcomes [323]. The researchers behind Graille envision its deployment in museums to enhance the interpretation of exhibits. However, specific details regarding the user interface in these domains remain undisclosed. Additionally, language barriers hinder access to comprehensive information about both the Graille Display and corresponding user interfaces.

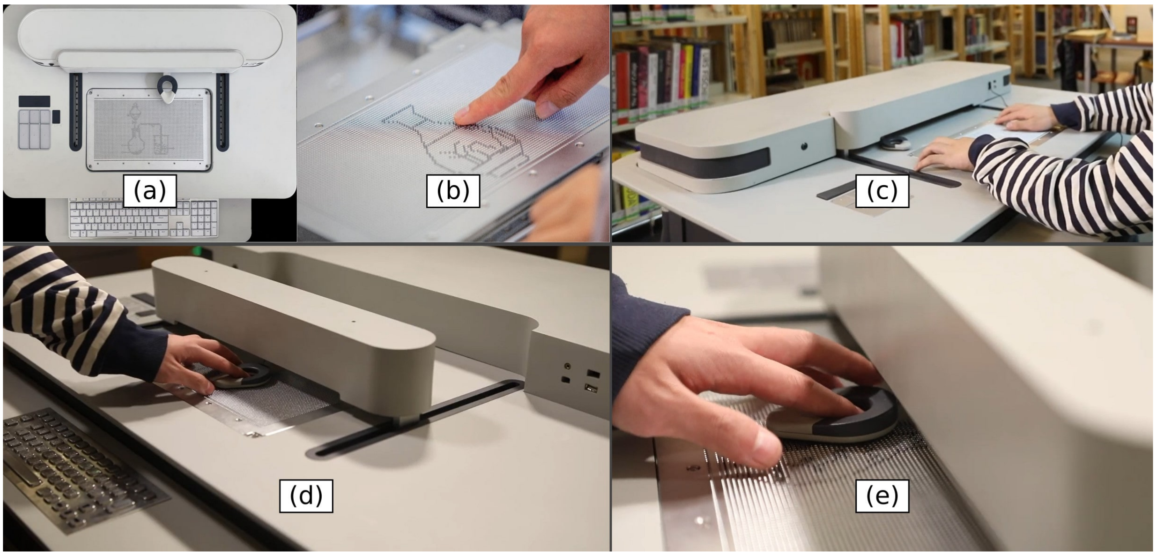

Figure A.15.: The Graille Display from Tsinghua University: (a,b,c). The ring guidance slider mechanism (d,e) [323]. *A Modern Graille* - `https://www.youtube.com/watch?v=pliMPr0Rdcw`

POLYMER BRAILLE

Polymer Braille Inc., in collaboration with North Carolina State University, has undertaken the development of a Real-Time Programmable Matrix (2DRTP) display, leveraging electroactive polymer technology combined with piezoelectric actuators [144] (figure A.16). By 2016, a prototype of the 'Polymer Braille device' emerged, featuring a tactile array comprising 360 pins arranged in a 12 x 30 configuration [63]. However, essential insights into the user interface and associated software remained undisclosed. While promising, unfortunately, the project's activity dwindled after 2016, and no commercial display product has been unveiled until now.

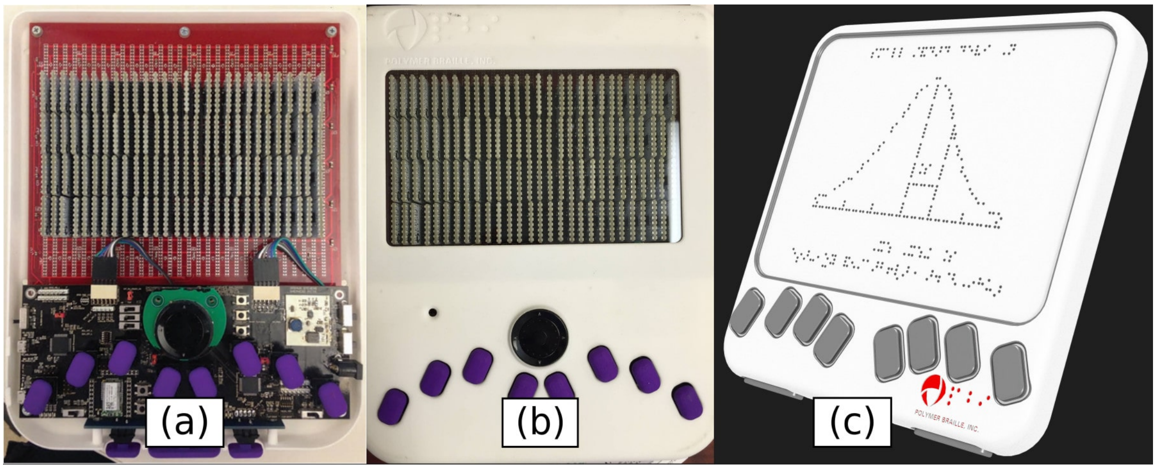

Figure A.16.: The Polymer Braille device from Polymer Braille Inc. The prototype developed with North Carolina State University (a,b) [63]. Conceptual representation of the device (c) [144].

BLINDPAD

The BLINDPAD project [75], launched in 2014, was dedicated to the creation and field-testing of a pioneering Personal Assistive Device called **BlindPAD**. Leveraging cutting-edge touch-based technologies, BlindPAD aimed to empower visually impaired individuals with access to graphical content, fostering knowledge, independence, and an improved quality of life.

In 2017, the BLINDPAD project achieved a significant milestone with the development of its first prototype [326] (figure A.17). This initial iteration of BlindPAD incorporated electromagnetic (EM) actuators within a 4x4 pin-matrix configuration, generating diverse static configurations while minimising unwanted interactions between neighbouring taxels. The micro-fabricated coils, forming an array, produced localised magnetic fields, enabling pin movements of up to 0.5 mm. The prototype successfully demonstrated a considerable holding force of 25 mN, which proved pivotal for its functionality. User testing involving discriminating 4x4 symbols yielded promising results, with correct response rates higher than 90 per cent, affirming the prototype's potential effectiveness in providing graphical content accessibility for visually impaired individuals [326].

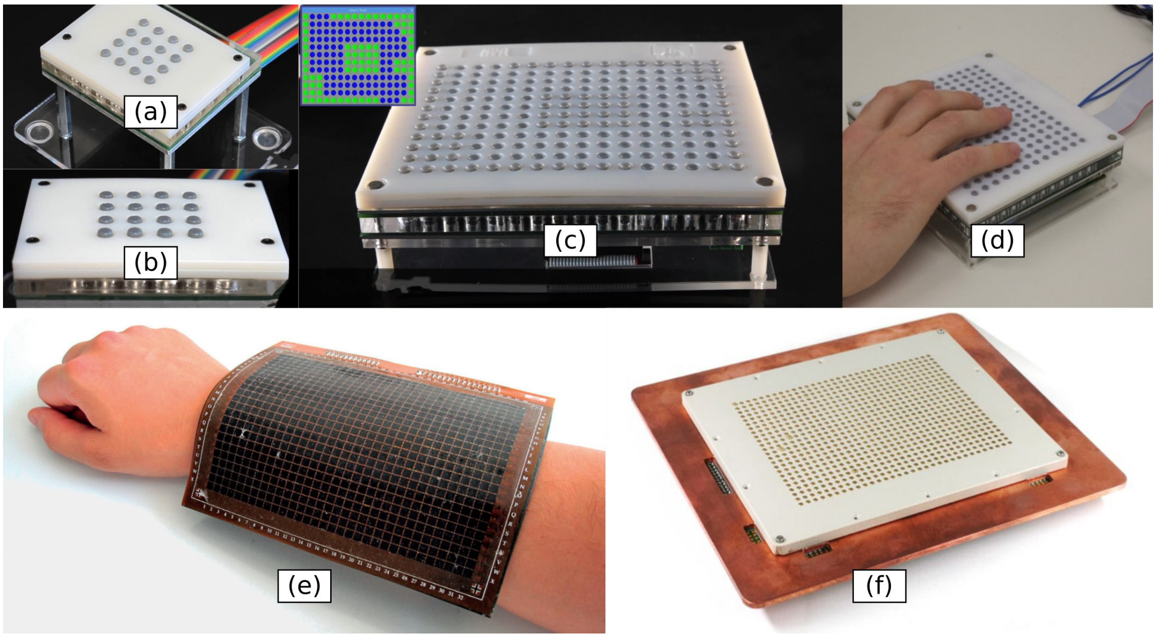

Figure A.17.: The different BlindPad prototypes from the BLINDPAD Project. 4x4 pin-matrix version (a,b) [326]. 16x12 pin-matrix version (BlindPad-KiT) (c,d) [325]. SMP flexible membrane with flexible PCB and pin-heaters (e) [31]. 32x24 pin-matrix version (BlindPad-SMP) (f) [30, 32].

Later on, the prototype evolved to encompass a larger device housing a 16x12 taxel pin-matrix (192 taxels in total) spanning an area of 124x94 mm [325], named "Keep in Touch" (KiT). This marked the key advancement in the BlindPAD's development. Notably, each pin possessed a 4mm diameter, a stroke raise of 0.55mm, and a pin spacing of 8mm, closely resembling the standard LEGO dot spacing. Importantly, this unique spacing sets it apart from other devices. The device features a refresh rate of less than 2 seconds and weighs only 870 grams [325, 186]. Past research underscores the efficacy of LEGO brick spacing in forming robust mental representations through combined visual and tactile cues [297]. The choice of these dimensions aimed to uphold an aspect ratio of 4/3, a familiar reference from visual graphics [54].

One of the primary applications of the BlindPAD was to facilitate tactile exploration of maps, including indoor floor plans [54]. The authors focused on leveraging sensory feedback to foster the construction of a cognitive map rather than merely providing navigational information for obstacle detection. Remarkably, results indicated that individuals who were totally and congenitally blind could effectively utilise allocentric map representations, showcasing the prototype's efficacy. Moreover, this iteration of the BlindPAD served as a valuable tool to enhance other fundamental spatial skills, such as distance discrimination. Frequently employed daily, this perceptual task spans from measuring geometrical shapes in educational settings to estimating distances between cars to avoid collisions [186]. In addition to its primary research in navigation and mobility support, the 16x12pin BlindPAD prototype featured engaging applications, including a dynamic tactile Pong game [325].

As part of the same project trajectory, a subsequent iteration of the BlindPAD concept emerged in 2017, named "BlindPAD-SMP" [31, 33, 30, 32]. This evolved prototype boasts an expanded scale compared to its predecessors, featuring a large haptic matrix of 32 x 24 metal pins, distinctively characterised by pins with a 3mm diameter and spacing of 4mm. The integration of a flexible shape memory polymer (SMP) membrane, 40 µm in thickness, enables localised heating for pin elevation [33, 30]. Notably, each of the 768 individual pins can be controlled, requiring up to 2.5 seconds for a complete refresh cycle, culminating in a cumulative refresh rate of approximately 17 seconds [29]. Like its predecessors, empirical tests involving the discernment of 4x4 symbols yield favourable outcomes [31, 32]. Regrettably, this iteration marked the conclusion of the BlindPad project's developmental journey, and its corresponding website has become inaccessible due to its closure.

In summary, the evolution of the BlindPAD's prototypes demonstrated significant strides in enhancing its functionality, offering a wide range of applications catering to the unique needs of visually impaired individuals. However, it is essential to note that this project and device were subsequently discontinued and never launched to market.

DOT PAD

Since 2018, Dot Co. Ltd has been actively developing the **Dot Pad** device, which has garnered significant attention and undergone substantial advancements in recent years [145, 71] (figure A.18). The Dot Pad comprises distinct sections, including one dedicated to text with 20 8-pin Braille cells and another for graphics featuring 300 Braille cells in a 60 x 40-pin matrix (2400 pins). This innovative device leverages electromagnetic Braille actuators with rotating latch structures, offering portability and a lightweight design compared to conventional Braille actuators while maintaining real-time refresh capabilities [163, 164]. It is noteworthy that while extensive research has been conducted on its pin mechanism, the Dot Pad has yet to explore user interface investigations.

While the DotPad's full development and readiness are still to be determined, it supports various applications, including maps, photographs, diagrams, charts, and drawings. It has facilitated co-design sessions, translating visual vector diagrams for blind users [91], and is integrated into the IMAGE Project at McGill University, representing objects from photographs as tactile patterns in layers [178]. However, this integration is still in its early stages, with no published results yet.

The DotPad demonstrated advanced UI features at CSUN 2022, including panning, zooming, line thickness control, and inverted braille filter representation [88]. At SightCity 2023, a collaborative drawing app with Apple was showcased, enabling real-time drawing on an iPad with simultaneous output on the DotPad, underscoring its versatility in tactile content creation. Ongoing developments are expected to expand its UI and application capabilities in the coming years.

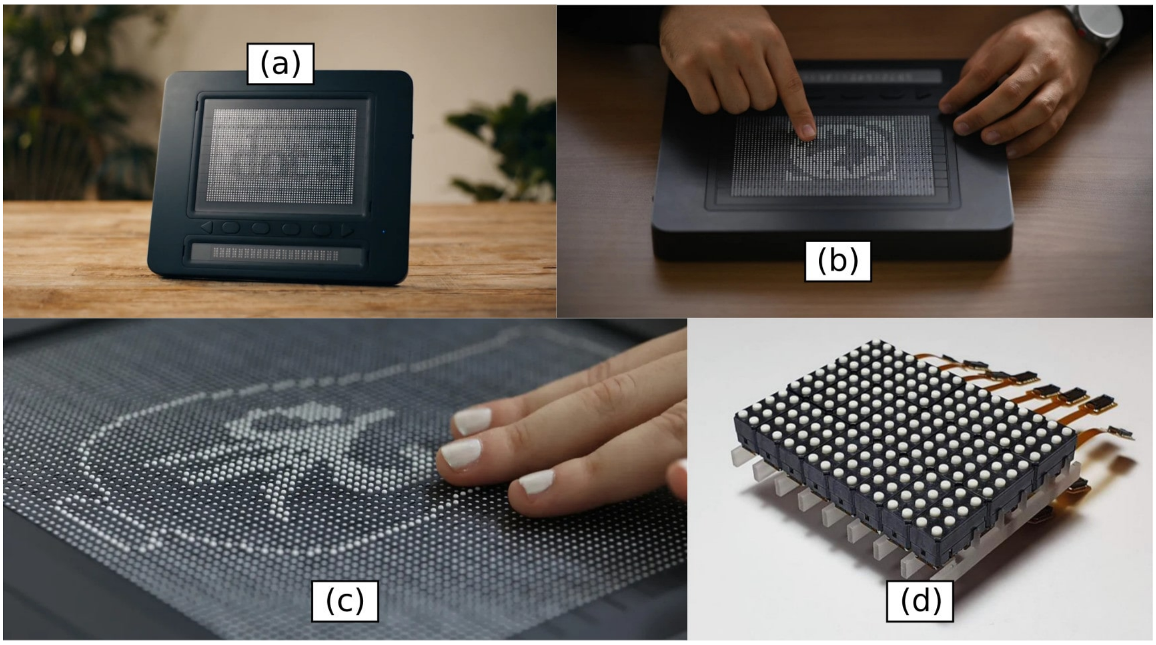

Figure A.18.: The Dot Pad display from Dot Co (a,b,c) [145, 71]. Electromagnetic Braille actuators (d) [164].

CANUTE 360

Canute 360 is a multi-line refreshable braille display developed by Bristol Braille Technology CIC. Released in 2019, it resulted from over six years of development [291] (Figure A.19). The device features nine braille lines with 40 cells each, totalling 360 cells. The pins are arranged in a non-equidistant configuration, with a dot spacing of 2.5mm and a diameter of 1.2mm [292]. Its refresh mechanism updates each line individually, approximately 16 seconds to refresh all lines, with intelligent rendering that refreshes only changed lines. While the pin-mechanism details are undisclosed, available material suggests it utilises an innovative mechanism likely actuated by conventional miniaturised gear motors [191]. Notably, the Canute 360's open-source user interface, built in Python, encourages user-driven expansion [55]. It supports various domains, including book reading, music, mathematics, tabular data, and tactile graphics. Further, it stands out as a portable solution with an SD-card port for file reading and a desktop menu UI for enhanced usability.

Bristol Braille Technology introduced the Canute Console [293], an extension for the Canute 360. It consists of a Linux workstation with a pull-out QWERTY keyboard, a fold-up 13-inch monitor, and a Raspberry Pi 400, designed to facilitate collaboration between braille and sighted users. The extension supports applications like programming, word processing, drawing diagrams in Braille ASCII, generating word searches, creating tactile SVG files, rendering spreadsheets, and viewing LaTeX math. It also includes games like a city exploration map, a tactile football pitch game, and a reimagined 'Snake'. Additionally, it enables presenting spatial information to both blind and sighted users using standard Linux tools like Pandoc and LibreOffice, displaying data simultaneously on a slide show and the Braille display.

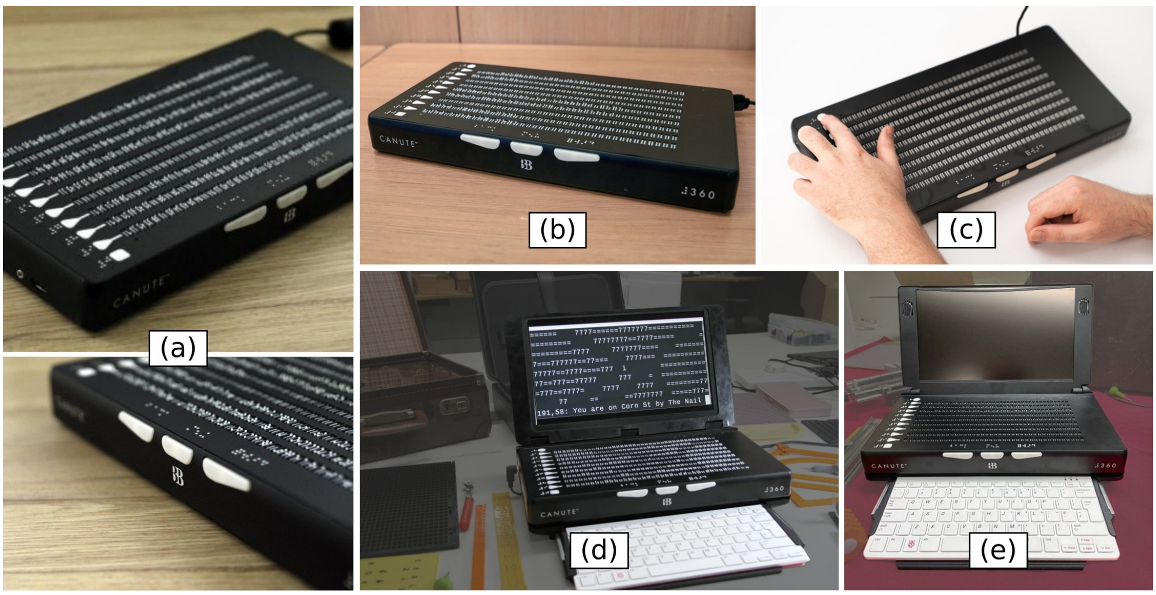

Figure A.19.: The Canute 360 standalone (a,b,c) [291]. The Canute Console (d,e) [293].

TACTILE PRO

Since 2008, Gachon University and Power Contents Technology Co., Korea, have collaborated on developing a 2DRTP display known as **Tactile Pro** [192] (figure A.20). The initial phase of this research focused on hardware development, resulting in a prototype consisting of 432 pins using tiny ultrasonic linear actuators (TULA) in a 24x18 grid configuration [154, 155]. The pins were spaced 5mm apart, with a 2mm vertical motion control. Subsequently, in 2019, the prototype transitioned into a product release, featuring a 40x56 pin-matrix size, a 0.3-second refresh rate, and a 3mm pin-spacing that, while closer, does not fully comply with the established braille standards [53, 300]. Remarkably, the 40x56 pin-matrix size features an unconventional aspect ratio, with a width smaller than the height, a rarity in 2DRTP devices.

Regarding user interface software, research efforts have led to the development of an eBook (DAISY) reader application [167, 168] capable of rendering extensive text and visuals. This application addresses the challenge of navigating lengthy texts (using panning operations) and offers customised Text-to-Speech (TTS) support. Graphics are processed using computer vision techniques, emphasising variations in grey levels and central object extraction, enhancing and simplifying recognition for BVI people [220]. Notably, the software enables the split of the tactile screen, such as dedicating the first two columns to display navigation context cues while the remaining screen space presents the actual text. The software has been demonstrated with conceptual simulations featuring 32x24 and 50x50 pin-matrix sizes, but is designed to be adaptable to various other pin-matrix sizes.

Since 2019, it seems that development and research on the Tactile Pro display have concluded, with no new updates or developments reported.

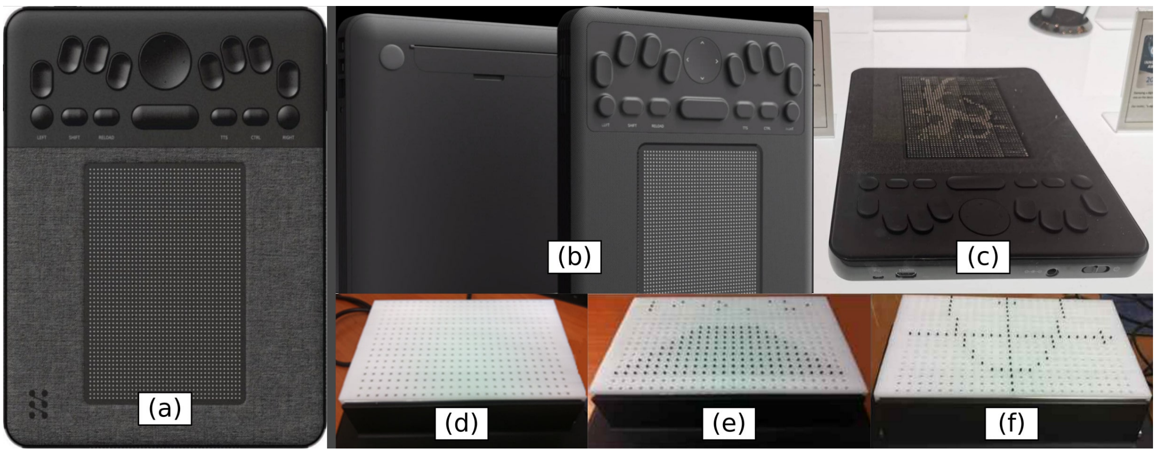

Figure A.20.: The Tactile Pro from Power Contents Technology (PCT). The latest (40x56 pin-matrix) release (a,b,c) [192]. The 2011 (24x18 pin-matrix) prototype version (d,e,f) [154, 155].

GRAPHITI

In 2016, Orbit Research and the American Printing House launched a collaboration to develop the **Graphiti**, a refreshable tactile pin-matrix device [244, 247] (figure A.21). The Graphiti features 2400 independently addressable pins arranged in a 60 x 40 configuration, capable of blinking at variable rates for dynamic visual displays and user engagement. Its tactile surface supports touch interaction, enabling functions like scrolling, panning, and multi-touch gestures. With a refresh rate of 5 seconds for the entire page, the pins refresh sequentially from top to bottom, ensuring a seamless tactile experience. Additionally, a set of buttons on the bottom frame enhances user control and interaction.

One distinguishing feature of the Graphiti is the capability to adjust the height of each pin individually, allowing for a total of 4 different heights. This feature introduces a non-binary dimension to tactile representation, potentially allowing for the conveyance of 3D information. Compared to other devices in the overview, the Graphiti employs a slightly larger pin spacing of 4mm. This pin-spacing may have implications on its ability to represent Braille characters in accordance with Unified Braille norms defined by the Braille Authority of North America [53]. Furthermore, it is worth noting that the recognition and acceptance of refreshable tactile Pin-matrix displays often improve when pin spacing is reduced while simultaneously increasing the pin array size. Therefore, having a pin spacing higher than the recommended norm may affect its overall effectiveness and acceptance in the context of tactile display technology [111, 137].

The first version of the Graphiti was officially released in 2019/2020, signifying an important milestone in the advancement of tactile technology. With the potential to profoundly impact inclusivity and expand tactile interaction capabilities, this device warrants further investigation and evaluation in assistive technology. Notably, the Graphiti offers remarkable versatility, capable of functioning as a Tactile Monitor with HDMI video input simplicity while also serving as a stand-alone device with the capability to view, create, and edit pictures, thereby enhancing its appeal and usability across various contexts.

The Graphiti boasts a wide array of applications, allowing users to view pictures in formats like JPEG, PNG, SVG, and PDF, as well as diagrams, graphs, maps, logos, and emojis. With a focus on STEM documents in fields like chemistry, astronomy, biology, and mathematics, the device offers an interactive and tactile approach to data visualisation and concept comprehension. Additionally, the Graphiti brings entertainment to the forefront with live interactions in Tetris-based games and touch-based drawing applications, providing users with an engaging and immersive experience for creative pursuits and recreational enjoyment.

The Graphiti has been the subject of several research studies, showcasing its versatility and potential applications. One study focused on implementing a 15x15 crossword puzzle, leveraging the tactile capabilities of the Graphiti while incorporating audio feedback to convey distribution information, effectively separating the spatial component from its textual content [242, 243]. In another investigation, researchers developed a protein molecule viewer using Visual Molecular Dynamics software, transforming 3D representations of protein molecules into variable-height tactile views on the Graphiti [269]. Furthermore, other studies explored the advantages of using 2DRTP devices compared to tactile graphics. Despite Graphiti's 2400 pins, it was found that this pin total might still fall short in conveying the same amount of information as an equivalent standard tactile graphic [137]. These studies collectively shed light on Graphiti's potential and limitations, offering valuable insights for future research and practical applications.

In 2022, at the 37th Annual CSUN Conference on Technology for People with Disabilities, Orbit Research unveiled the **Graphiti Plus** [245, 246], representing an enhanced version of the original Graphiti device. The key differentiator between the Graphiti and Graphiti Plus lies in adding a single-line Braille display featuring 40 Braille cells thoughtfully positioned at the bottom of the device, bearing similarities to the Dot Pad's design [145]. This design addresses the limitation of the standard Graphiti, which could not previously output Braille text due to its larger pin spacing [53]. Additionally, the Graphiti Plus has an ergonomic Perkins-style 8-key braille keyboard featuring four directional arrows and a select key, providing intuitive and effortless navigation for users. This latest iteration of the Graphiti series represents a significant advancement, catering to the diverse needs of users and furthering the device's potential impact in the field of assistive technology.

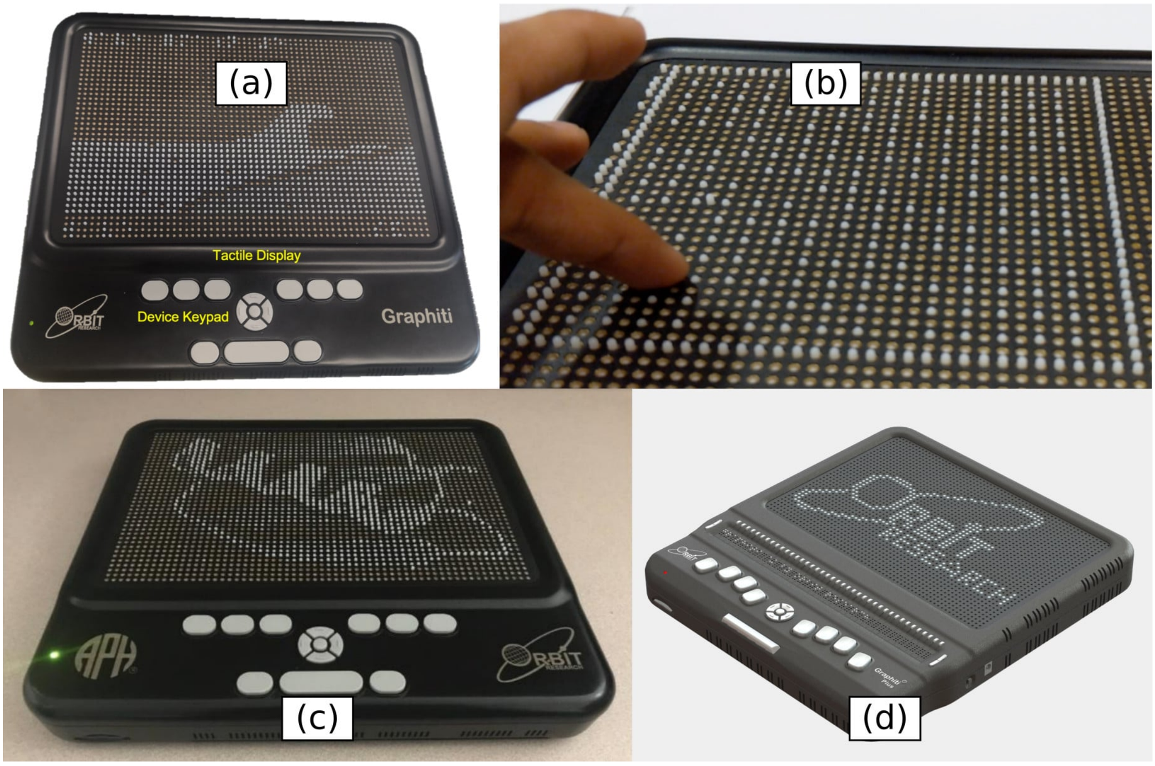

Figure A.21.: The Graphiti series from Orbit Research and the American Printing House (APH). The standard Graphiti display (a,b,c) [137, 269, 243]. The Graphiti Plus display (d) [245].

BRAILLE PAD

Starting in 2021, 4Blind undertook the development of a 2DRTP display denoted as the **Braille PAD** [4] (figure A.22). This innovation distinguishes itself from standard 2DRTP displays by functioning as an integrated solution that can be used as a display and a standalone device. Featuring a grid consisting of 1850 translucent pins (50 x 37), its primary application domain focuses on image visualisation. Despite its substantial potential, the limited availability of comprehensive documentation and research contributions hinders a thorough understanding, including essential aspects such as pin refreshment rates and insights into user interface intricacies. Nevertheless, the project remains active, with expectations for forthcoming disclosures to enhance our understanding.

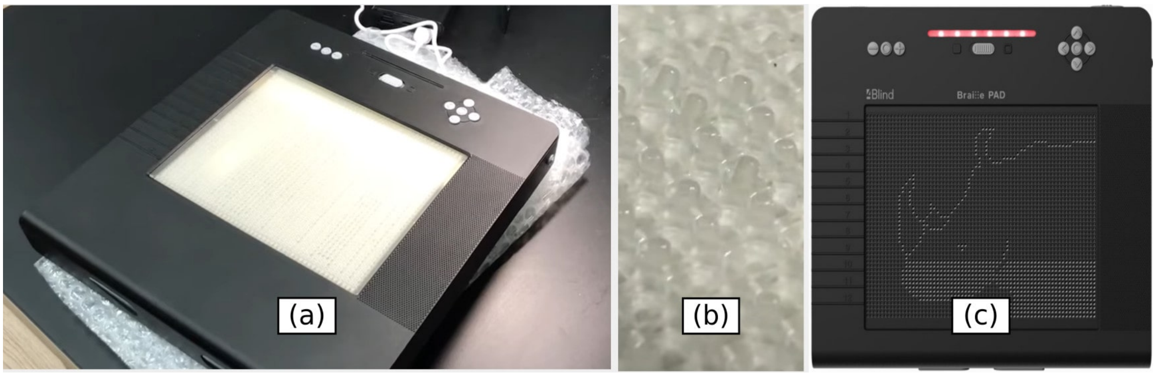

Figure A.22.: The Braille PAD device from 4Blind. The developed prototype with translucent pins (a,b). Envisioned digital representation of the device (c) [4].

TACILIA

A collaborative effort between IIT Delhi, UCL, and the Global Disability Innovation Hub formed the development of **Tacilia** in 2021 [299] (figure A.23). The prototype featured 729 pins arranged in a grid of 27 by 27, with a pin spacing of 2.5mm [34]. These pins were constructed from shape memory alloys, specifically thin monolithic sheets of Nitinol, known for their ability to bend when subjected to heat. To facilitate pin actuation, the prototype employed a hot air-jet pencil capable of elevating the Nitinol pins by up to 0.4mm. However, this height fell short of meeting the requirements outlined in Braille standards [256, 53, 300]. Each pin takes 1 second to rise, and users wait 3 seconds for the pins to cool to a safe temperature before interaction.

Users were able to discriminate small symbols of 5x5 size effectively using the Tacilia prototype. Additionally, pixel art tactile graphics were found to be comprehensible and clear on the tactile display, confirming its suitability for designing basic tactile shapes and line segments that constitute complex tactile graphics [35]. Tacilia was also employed to draw alphabet letters with the hot air pencil prototype, shedding light on users' ability to draw freehand shapes through tactile sensations [34, 36].

While not currently a 2DRTP display, Tacilia aims to incorporate an array of micro-heaters beneath each pin for selective heating to raise the pins, thereby transitioning into a refreshable device. The Tacilia project is actively pursuing commercialisation and market entry [114].

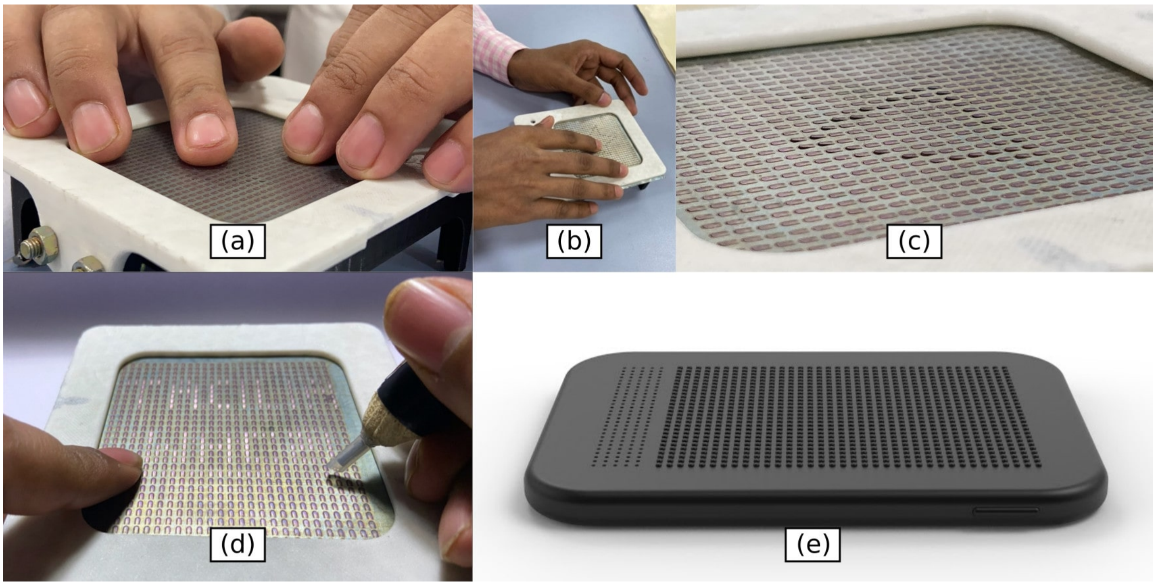

Figure A.23.: The Tacilia display: (a,b,c,d) Proof of concept 2021 prototype [34, 35]. (e) Envisioned digital representation of the device [299]

MONARCH

The **Monarch**, originally introduced as the Dynamic Tactile Device (DTD) in 2022 at CSUN, represents a collaborative effort between HumanWare, the American Printing House, and the National Federation of the Blind (NFB) [141] (figure A.24). This innovative device boasts a 96x40 matrix equipped with 3,840 pins, employing refreshable pin technology reminiscent of the Dot Pad (around 3 seconds for a full refresh), developed by Dot Incorporation [163, 164]. Distinctively, the Monarch does not operate as a tactile display, as is common among other 2DRTP devices, but as a stand-alone device with its own operating system. An intriguing feature is its finger recognition capability, which can recognise double-tap gestures [142]. The fingertip technology is achieved through a sensor, distinguishing it from touch surface-based approaches used in other 2DRTP displays.

The main goal of the Monarch is to empower students with BVI by granting them access to educational tactile graphics, including full access to the American Printing House's online TGIL (Tactile Graphic Image Library) [1]. Furthermore, at SightCity 2023, the Monarch showcased its versatility by presenting a word text editor and its tactile graphics viewing capabilities. While the device features an audio jack and a microphone, comprehensive audio support has not yet been demonstrated and explored. In terms of broader applications and research, due to its novelty and recent launch, there is currently no published research available. However, during SightCity 2023, the device already demonstrated support for user interactions such as zooming, panning, and page navigation. Additionally, the Monarch is equipped with a vibration actuator for user communication, akin to the DotPad. In summary, the Monarch exhibits significant potential, yet its software development and further exploration of its capabilities remain ongoing as it evolves beyond its early stages.

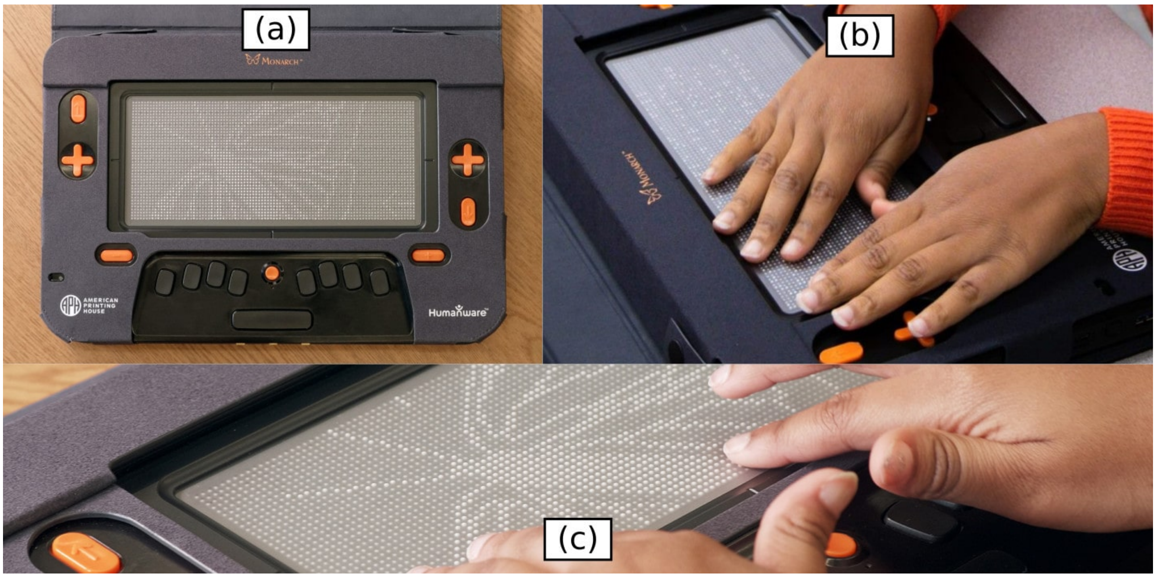

Figure A.24.: The Monarch device from APH and HumanWare: (a,b,c) [141]

TACTONOM

Since 2017, Inventivio GmbH, Germany, has developed the 2DRTP display known as **Tactonom** [116] (figure A.25). This display boasts a unique 10,472 pins (119x88 pin-matrix), providing exceptionally high resolution within this technology. Each pin is spaced 2.5 mm apart with a pin diameter of 1.35 mm. Notably, it differs from other devices on this list by incorporating a top-facing camera that recognises fingertip positions for precise interaction. The pin mechanism relies on metal beads positioned beneath each pin, manipulated by a column of magnets spanning the entire screen. When the magnets traverse the screen, the pins either lower or remain elevated on their respective beads. This cost-effective approach contrasts with state-of-the-art technology, although it results in a longer refreshment time (10 seconds for the full screen).

In contrast to other technologies emphasising pin mechanism enhancements, Inventivio has recently concentrated primarily on software development. This effort yielded a suite of applications, including a web browser, email client, file explorer, desktop control, graphics viewer, widget library, word editor, spreadsheet software, open-street map viewer, and entertainment games. To mitigate the long 10-second refresh rate, the software leverages real-time audio processing to introduce dynamic interactions. The primary emphasis of this dissertation centred on the Tactonom device, which debuted in the market in 2024.

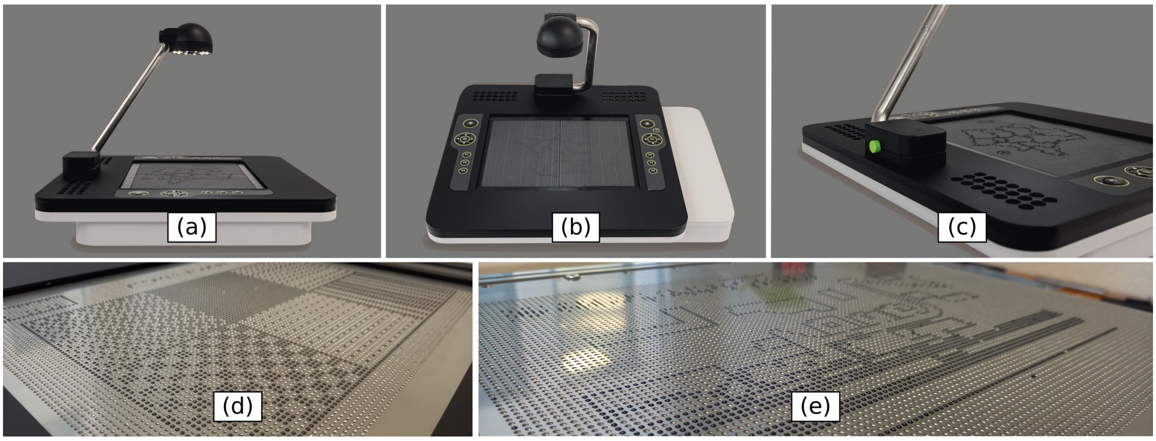

Figure A.25.: The Tactonom display from Inventivio GmbH: (a,b,c) [116]. The tactile 119x88 pin-matrix surface (d,e).

In addition to the 2DRTP devices discussed in this analysis, it is worth noting that there are several other fitting devices within this category. However, certain limitations hindered their inclusion in this study. Firstly, a scarcity of comprehensive information and language barriers restricted the collection of accurate data. Additionally, small-scale projects and devices with small tactile screens, which were incapable of effectively conveying 2D aspects to individuals with BVI, were excluded from this study as they did not significantly contribute to the 2DRTP analysis and development.

A.2. 2DRTP ANALYSIS: HARDWARE CHARACTERISTICS

Table A.1.: Hardware user interface characteristics of 2DRTP displays.

2DRTP-Device	Pins Dimension[A]	Size[B]	Pin[C]	Weight[D]	Rate[E]	Atypical[F]
DMD 12060	7200 (120 × 60)	648.00	3.0	20	0.05	Ring sensor
GWP	384 (24 × 16)	34.56	3.0	—	> 1	—
NIST display	3621 (71 × 51)	229.12	2.54	—	0.03	—
KGS DV-1	768 (32 × 24)	69.12	3.0	2.2	20	—
KGS DV-2	1536 (48 × 32)	88.55	2.4	1.5	20	—
ITACTI	8192 (128 × 64)	512.00	2.5	5.5	0.143	ER fluid
OUV3000	3072 (64 × 48)	239.90	2.8	10	0.045	—
BrailleDis 9000	7200 (120 × 60)	450.00	2.5	8	4.5	Touch surface (the first)
Shimada	3072 (96 × 32)	174.00	2.4	—	20	Scroll bars
MobileBrailleDis	960 (32 × 30)	60.00	2.5	0.6	4.5	Wii remote
BrailleDis 7200	7200 (120 × 60)	450.00	2.5	5.5	20	Navigation bar
Tactis 100	600 (12 × 50)	66.24	2.5	1.0	0.2	Multi line display
Tactis Table	12000 (120 × 100)	750.00	2.5	6.0	0.125	—
Tactis Walk	2400 (60 × 40)	150.00	2.5	2.5	0.125	—
Polymer Braille	360 (30 × 12)	—	—	—	—	—
Graille	7200 (120 × 60)	450.00	2.5	—	0.03	Guidance ring
BrailleDis 6240	6240 (104 × 60)	390.00	2.5	4.0	20	—
Hyperflat	3648 (76 × 48)	228.00	2.5	2.3	20	—
BlindPAD-KiT	192 (16 × 12)	116.56	8.0	0.87	0.52	LEGO Size
BlindPAD-SMP	768 (32 × 24)	125.73	4.0	5.04	0.06	Flexible SMP
Dot Pad	2400 (60 × 40)	150.00	2.5	1.2	0.33	Additional Braille-line
Canute 360	2160 (80 × 27)	336.67	2.5	2.8	0.06	Multi line display
Tactile Pro	2240 (40 × 56)	201.60	3.0	—	3.33	-
Graphiti	2400 (60 × 40)	400.00	4.0	1.8	0.2	Multi pin height
Tactile2D	1872 (48 × 39)	116.40	2.5	—	20	—
Braille PAD	1850 (50 × 37)	197.23	3.3	1.59	—	Translucent pin
Tacilia	729 (27 × 27)	43.82	2.5	—	—	Hot-air heaters
Monarch (DTD)	3840 (96 × 40)	240.00	2.5	2.1	0.33	—
Tactonom Pro	10472 (119 × 88)	664.54	2.5	9.6	0.1	Top-facing camera

(—): Information is unavailable.

[A] Pin Dimensions: Total pins, width × height.
[B] Surface Size: Square millimetres.
[C] Pin Spacing: Millimetres.
[D] Weight: Device weight in Kilograms.
[E] Refreshment Rate: Hertz.
[F] Atypical UI Design: Unique hardware characteristics.

A.3. 2DRTP ANALYSIS: AUDIO-TACTILE INPUT-OUTPUT CAPABILITY

Table A.2.: Audio-Tactile input and output capabilities of 2DRTP displays.

2DRTP-Device	Buttons	Finger[A]	Gestures	M-touch[B]	Audio Support[C]	Grounding[D]
DMD 12060	—	yes	yes	yes	—	dependent
GWP	yes	—	—	—	—	dependent
NIST display	yes	—	—	—	—	dependent
KGS DV-1	yes	yes	—	yes	—	dependent
KGS DV-2	yes	yes	yes	yes	—	dependent
ITACTI	—	yes	—	—	—	dependent
OUV3000	—	—	—	—	—	dependent
BrailleDis 9000	yes	yes	yes	yes	—	dependent
Shimada	yes	yes	—	—	—	dependent
MobileBrailleDis	—	yes	—	—	yes	dependent
BrailleDis 7200	yes	yes	yes	yes	—	dependent
Tactis 100	yes	—	—	—	—	dependent
Tactis Table	yes	—	—	—	—	dependent
Tactis Walk	yes	—	—	—	—	dependent
Polymer Braille	yes	—	—	—	—	dependent
Graille	yes	—	—	—	yes	independent
BrailleDis 6240	yes	yes	yes	yes	—	dependent
Hyperflat	yes	yes	yes	yes	—	dependent
BlindPAD-KiT	—	—	—	—	—	dependent
BlindPAD-SMP	—	—	—	—	—	dependent
Dot Pad	yes	—	—	—	—	dependent
Canute 360	yes	—	—	—	yes	independent
Tactile Pro	yes	—	—	—	yes	independent
Graphiti	yes	yes	yes	yes	—	independent
Tactile2D	yes	yes	yes	yes	—	independent
Braille PAD	yes	—	—	—	—	independent
Tacilia	—	—	—	—	—	dependent
Monarch (DTD)	yes	yes	—	—	—	independent
Tactonom Pro	yes	yes	—	—	-	dependent

(—): Absence and lack of information.

[A] Finger recognition: Can recognise the finger/hand.
[B] Multi-touch: Supports multi-touch interaction.
[C] Audio: Support text-to-speech or other sounds (includes custom speakers).
[D] Grounding: If the 2DRTP device is a display-only (dependent) or a standalone (independent).

A.4. 2DRTP ANALYSIS: DOMAIN COVERAGE

Table A.3.: Domain coverage of UI of 2DRTP displays.

2DRTP-Device	Text	Image	Graph[A]	O&M[B]	Edu.[C]	Enter.[D]	Drawing	Browser[E]
DMD 12060	yes	yes	yes	—	—	—	yes	yes
GWP	—	yes	—	—	yes	—	—	—
NIST display	—	yes	—	—	—	—	—	—
KGS DV-1	—	yes	—	—	yes	yes	yes	—
KGS DV-2	yes	yes	yes	—	—	yes	yes	—
ITACTI	yes	yes	—	—	—	—	—	—
OUV3000	—	yes	—	—	—	—	—	—
BrailleDis 9000	yes	yes	yes	yes	—	yes	—	—
Shimada	—	yes	—	—	—	—	—	—
MobileBrailleDis	—	—	—	yes	—	—	—	—
BrailleDis 7200	yes	yes	yes	yes	yes	yes	yes	—
Tactis 100	yes	—	—	—	—	—	—	—
Tactis Table	—	yes	—	—	—	—	—	—
Tactis Walk	—	yes	—	—	—	—	—	—
Polymer Braille	—	—	—	—	—	—	—	—
Graille	yes	yes	—	—	—	—	—	—
BrailleDis 6240	yes	yes	yes	—	yes	—	yes	—
Hyperflat	yes	yes	—	yes	yes	—	—	—
BlindPAD-KiT	—	—	—	yes	—	yes	—	—
BlindPAD-SMP	—	yes	—	—	—	—	—	—
Dot Pad	—	yes	—	—	—	—	yes	—
Canute 360	yes	—	—	—	—	yes	—	—
Tactile Pro	yes	yes	—	—	—	—	—	—
Graphiti	—	yes	yes	yes	yes	yes	yes	yes
Tactile2D	yes	yes	—	—	yes	—	—	—
Braille PAD	—	—	—	—	—	—	—	—
Tacilia	—	yes	—	—	—	—	yes	—
Monarch (DTD)	yes	yes	—	—	—	—	—	—
Tactonom Pro	yes	yes	—	yes	yes	yes	—	yes

(—): Absence and lack of scientific evidence.

[A] Graphic manipulation: Dynamically manipulate (e.g. move) elements in graphics.
[B] Orientation and mobility: From floor plans or geo-data viewer to obstacle detection interface.
[C] Education: Leveraging education materials and work graphics.
[D] Entertainment topics (includes Games).
[E] Browsing the Web (Web Browser).

A.5. 2DRTP ANALYSIS: GRAPHIC INTERACTIVE UI OPERATIONS

Table A.4.: Interactive UI elements support of 2DRTP displays

2DRTP-Device	Pan	Zoom	E.read[A]	E.edit[B]	Focus[C]	Region[D]	Filter[E]	Menu[F]
DMD 12060	yes	yes	yes	yes	—	yes	yes	—
GWP	yes	yes	—	—	yes	—	—	—
NIST display	—	—	—	—	—	—	—	—
KGS DV-1	yes	—	—	—	yes	—	—	—
KGS DV-2	yes	yes	yes	yes	yes	—	—	—
ITACTI	—	—	—	—	—	—	—	—
OUV3000	—	—	—	—	—	—	—	—
BrailleDis 9000	yes	yes	—	—	yes	yes	—	—
Shimada	yes	yes	yes	—	—	—	—	—
MobileBrailleDis	yes	yes	yes	—	—	yes	—	—
BrailleDis 7200	yes	yes	yes	yes	yes	yes	yes	yes
Tactis 100	—	—	—	—	—	—	—	—
Tactis Table	—	—	—	—	—	—	—	—
Tactis Walk	—	—	—	—	—	—	—	—
Polymer Braille	—	—	—	—	—	—	—	—
Graille	—	—	—	—	—	—	—	—
BrailleDis 6240	yes	yes	yes	yes	yes	yes	yes	yes
Hyperflat	yes	yes	yes	yes	yes	—	—	—
BlindPAD-KiT	—	—	—	—	yes	—	—	—
BlindPAD-SMP	—	—	—	—	—	—	—	—
Dot Pad	yes	yes	—	—	—	—	yes	—
Canute 360	yes	—	—	—	—	yes	—	yes
Tactile Pro	yes	yes	—	—	—	yes	—	yes
Graphiti	yes	—	—	—	yes	—	yes	yes
Tactile2D	yes	yes	yes	yes	yes	yes	yes	—
Braille PAD	—	—	—	—	—	—	—	—
Tacilia	—	—	—	—	—	—	—	—
Monarch (DTD)	yes	yes	—	—	—	—	—	yes
Tactonom Pro	yes	yes	yes	—	—	yes	yes	yes

(—): Absence feature or lack of scientific evidence.

[A] User can access/read elements displayed on the tactile surface.
[B] User can move/change specific elements on the tactile surface.
[C] UI can highlight a specific area/element on the tactile surface.
[D] UI can split the tactile surface into different regions.
[E] Filter the current view. Different ways to represent the content.
[F] UI has an OS which implements a menu with different options.

B. USER STUDIES DETAILS

This chapter provides the supplementary materials associated with the six key user studies included in this dissertation. Before delving into the materials for each specific study, we first present the layout of the SUS [60] and NASA-TLX [132] questionnaires used across all studies in which they were included.

System Usability Scale (SUS)

All user studies in this dissertation that included the System Usability Scale (SUS) used the standard SUS template [60] with minor adaptations. Following recommendations from [24], we replaced the word “cumbersome” in Question 8 with “awkward” for improved clarity. Additionally, Question 7 was adapted from “I would imagine that most people would learn to use this product very quickly” to “I think that most visually impaired people would learn to use this system very quickly” to reflect the context of assistive technology better. Participants rated each item on a 5-point Likert scale ranging from **Strongly Disagree (1)** to **Strongly Agree (5)**.

The SUS included the following items:

1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.
4. I think that I would need the support of a technical person to be able to use this system.
5. I found the various functions in this system were well integrated.
6. I thought there was too much inconsistency in this system.
7. I would imagine that most visually impaired people would learn to use this system very quickly.
8. I found the system very awkward to use.
9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with this system.

NASA Task Load Index (NASA-TLX)

The NASA Task Load Index (NASA-TLX) was used in selected user studies to assess perceived workload [132]. We employed the standard version of the questionnaire without any modifications. Participants rated each of the six workload dimensions on a scale from 0 (low) to 20 (high):

- **Mental Demand:** How mentally demanding was the task?
- **Physical Demand:** How physically demanding was the task?
- **Temporal Demand:** How hurried or rushed was the pace of the task?
- **Performance:** How successful were you in accomplishing what you were asked to do?
- **Effort:** How hard did you have to work to accomplish your level of performance?
- **Frustration:** How insecure, discouraged, irritated, stressed, and annoyed were you?

B.1. SUPPLEMENTARY MATERIALS – CHAPTER 4

Navigation through straight directions

Supplementary materials for Section 4.2 include the semi-interview guide.

Semi-structured Interview This semi-structured interview focuses on the user experience during the experimental usability study phase, which involved interaction with the audio-tactile user interfaces on the Tactonom Reader device. It is conducted after the testing phase and is designed to capture participants' personal experiences and reactions. Participants may have exhibited specific interactions or responses during the test, which will inform additional, tailored questions to explore these observations further.

Favourite Method:

1. What was your preferred navigation mode for locating tactile graphic elements?
2. Why did you prefer this method?
3. What was the most remarkable feature of this method?
4. What would you change or remove to improve it?

Least Preferred Method:

5. What was your least preferred navigation mode?
6. Why did you prefer this method the least?
7. If applicable: Did the method not work properly? Was the training insufficient? Were the selected elements especially difficult to locate?
8. What would you change or remove to improve it?

All Methods:

9. Do you think the methods were helpful in guiding blind or visually impaired users to specific elements in tactile graphics, or were they just additional features that most users might not use?
10. If not, which method would you use instead?
11. Why would that method be better? (Consider interface characteristics.)
12. Was the training session sufficient for all methods?
13. **Rate:** On a scale from 0 to 10, how would you rate each method's effectiveness in guiding users to specific tactile elements?

Tactonom Reader:

14. What would you improve in the Tactonom Reader user interface?
15. What is your opinion on 2D tactile graphics?

Navigation Strategy:

16. What is your usual strategy for locating an element in a new two-dimensional tactile graphic?
17. Does your strategy depend on the type of graphic? (e.g., floor plans vs. tables or diagrams)
18. After using these techniques, would you continue using your usual strategy, or would you switch to the new navigation modes if available?
19. Was the navigation-to-element menu intuitive to use? (You select the navigation option in the main menu, then select the element you want to navigate to.)
20. If not, how could this navigation menu be improved?
21. If applicable: How would you organise the graphical elements in the menu?

Additional Questions Additional questions regarding specific user interactions or reactions observed during the testing phase will be asked here to provide deeper insights into individual experiences.

SONOICE: combining sonification with voice

Supplementary materials for Section 4.3 include the semi-interview guide.

Semi-structured Interview This semi-structured interview focuses on the user experience during the experimental usability study phase, which involved interaction with the audio-tactile user interfaces on the Tactonom Reader device. It is conducted after the testing phase and is designed to capture participants' personal experiences and reactions. Participants may have exhibited specific interactions or responses during the test, which will inform additional, tailored questions to explore these observations further.

Navigation Mode Usefulness:

1. Was the navigation mode approach more helpful for locating elements in tactile graphics than the trial-and-error strategy?
2. Would you use one or more of the navigation modes yourself or recommend them to others? If not, do you think there is a general need for such or similar interaction modes to locate elements in complex tactile graphics?
3. In what context would you use the navigation modes and why?
4. Could the same or a similar principle be applied to other assistive technologies you use or know?
5. Have you worked with a similar navigation mode in other assistive technologies?

Favourite Method:

6. What was your preferred navigation mode for locating tactile graphic elements?
7. Why did you prefer this method?

Least Preferred Method:

8. What was your least preferred navigation mode for locating tactile graphic elements?
9. Why did you prefer this method the least?
10. If applicable: Did the navigation mode not work properly? Was the training insufficient? Were the selected elements challenging to locate?

Experience:

11. Does your preferred strategy depend on the type of graphic?
12. After gaining experience with the different navigation modes, would you stick to your usual strategy, or would you use the modes implemented in the Tactonom Reader if available?

(Additional follow-up questions may be added depending on specific participant responses or interactions observed during the session.)

B.2. SUPPLEMENTARY MATERIALS – CHAPTER 5

Exploring through trigger line tracing

Supplementary materials for the user study in Section 5.2 include the testing phase questionnaire and the semi-structured interview guide.

Testing Phase Questionnaire For each line chart, we asked the following questions:

- **Q1:** How many lines does the math plot graph have?
- **Q2:** Which line has the greatest number of different intersections? (That is, the line that connects with the most other lines.) If there is a tie, which lines are they? Note: it is not the line with the most total intersections, but the one with the most unique intersections.
- **Q3:** How many lines does the line identified in Q2 connect with?
- **Rate:** On a scale from 1 to 7, how complex is the math plot graphic, where 1 is very simple and 7 is extremely complex?

Semi-structured Interview This semi-structured interview focuses on the user experience during the experimental usability study phase, which involved interaction with the audio-tactile user interfaces on the Tactonom Reader device. It is conducted after the testing phase and is designed to capture participants' personal experiences and reactions. Participants may have exhibited specific interactions or responses during the test, which will inform additional, tailored questions to explore these observations further.

User Interface Usefulness:

1. Was the trigger user interface more efficient in differentiating math plots in tactile graphics than the standard user interface?
2. Would you use the trigger user interface or recommend it to others? If not, why?
3. What would you modify to make the user interface more efficient and effective in distinguishing lines of math plots?

User Interface Context:

4. In what context would you use the trigger user interface and why?
5. Have you ever interacted with similar user interfaces in other assistive technologies?

Additional Questions Additional questions regarding specific user interactions or reactions observed during the testing phase will be asked here to provide deeper insights into individual experiences.

Exploring through melodic line tracing

Supplementary materials for the user study in Section 5.3 include the testing phase tasks for each line chart and the semi-structured interview guide.

Testing Phase Tasks

During the testing phase, participants completed three types of tasks (Type 1, Type 2, and Type 3) for three pre-assigned lines on each line chart explored (sub-session).

The three task types were as follows:

- **Type 1:** Place your finger on the **"assigned-line"** energy share line. Follow this line with your finger from one edge to the other. Tell me when the line ends and starts.
- **Type 2:** Tell me the maximum and minimum points of the line.
- **Type 3:** How many different countries does this line intersect with?

The assigned lines for each line chart were as follows:

- **Line chart 1:** Argentina, Russia, Denmark
- **Line chart 2:** Madagascar, Luxembourg, Morocco
- **Line chart 3:** Netherlands, Italy, Ireland
- **Line chart 3:** Spain, Armenia, Bangladesh

Semi-structured Interview

This semi-structured interview focuses on the user experience during the experimental usability study phase, which involved interaction with the audio-tactile user interfaces on the Tactonom Reader device. It is conducted after the testing phase and is designed to capture participants' personal experiences and reactions. Participants may have exhibited specific interactions or responses during the test, which will inform additional, tailored questions to explore these observations further.

Overall Rating:

1. Which version of the user interface did you like better? Melodic user interface or standard user interface? Why? On a scale of 1 to 5, can you give a rating to each user interface on how it helped you understand the data line charts?

   Melodic: _____ **Standard:** _____ **R:** _________________________

Melodic User Interface:

2. On a scale from 1 to 5, how useful did you find the sound tracing functionality?
3. On a scale from 1 to 5, how useful did you find the use of musical notes to help distinguish different lines?
4. On a scale from 1 to 5, how useful did you find the feedback identifying maximum, minimum, and extreme points?

Graphics Exploration:

5. Have you ever interacted with similar user interfaces in other technologies?
6. On a scale from 1 to 5, how difficult or complex were the line charts you explored?
7. Would you use other methods or technologies to explore line charts?
8. After experiencing these user interfaces, would you prefer to continue with your usual approach, or use the melodic user interface to explore line charts?

Scalability:

9. Do you think the melodic user interface could be used in other contexts? Please name some.

Additional Questions Additional questions regarding specific user interactions or reactions observed during the testing phase will be asked here to provide deeper insights into individual experiences.

B.3. SUPPLEMENTARY MATERIALS – CHAPTER 6

Learning through tap-to-hear map-route exploration

Supplementary materials for the user study in Section 6.2 include the testing phase questionnaire and the semi-structured interview guide.

Testing phase questionnaire

We allow users complete freedom to explore all aspects of the travel route. To evaluate the strengths and weaknesses of the user interface and encourage users to reflect on how they learned the route, we pose the following questions:

- Can you perceive this route?
- Where does the route end?
- Can you switch to another line from your current station?
- What is nearby this station?
- How many underground lines can you switch to at this station?

Semi-structured Interview

This semi-structured interview focuses on the user experience during the experimental usability study phase, which involved interaction with the audio-tactile user interfaces on the Tactonom Pro device. It is conducted after the testing phase and is designed to capture participants' personal experiences and reactions. Participants may have exhibited specific interactions or responses during the test, which will inform additional, tailored questions to explore these observations further.

- **Effectiveness of Dynamic User Interface:**
  On a scale from 1 to 5, how effectively did the dynamic user interface support your understanding of travel routes in the network maps?
  (1: Not helpful, 5: Very useful).
  Please explain your rating.
- **Scalability:**
  Do you think this dynamic user interface could be applied in other contexts? Please name some examples, such as navigation in maps, flowchart exploration, or electronic circuit exploration.

Additional Questions Additional questions regarding specific user interactions or reactions observed during the testing phase will be asked here to provide deeper insights into individual experiences.

Learning through immersive map-route exploration

Supplementary materials for the user study in Section 6.3 include the semi-structured interview guide and the testing phase questionnaire (Paris and Madrid metro maps).

Semi-structured Interview

This semi-structured interview focuses on the user experience during the experimental usability study phase, which involved interaction with the audio-tactile user interfaces on the Tactonom Pro device. It is conducted after the testing phase and is designed to capture participants' personal experiences and reactions. Participants may have exhibited specific interactions or responses during the test, which will inform additional, tailored questions to explore these observations further.

1. Rate how well each user interface helped you understand routes. (1–5):
   Standard: [ ] Immersive: [ ]
2. How useful was the sound for lines with pitch changes? (1–5): [ ]
3. How useful were beep sounds at stops to show the number of connections? (1–5):
4. How useful were the points of interest sounds? (1–5): [ ]
5. How useful was splitting the route into detailed phases? (1–5): [ ]
6. How useful were the filter and mute options? (1–5): [ ]
7. How useful was it to render/hide the background lines? (1–5): [ ]
8. Rate the difficulty of Nuremberg's map. (1–5): [ ]
9. Rate the difficulty of Madrid's map. (1–5): [ ]
10. Rate the difficulty of Paris's map. (1–5): [ ]
11. Have you used similar technology before?
    Yes [ ] No [ ]
12. What would you normally use to explore and learn routes? (daily/usually)
    ____
13. Would you use this user interface instead of your old method? Does it add value?
    ____
14. Can this user interface be used in other areas or contexts?
    ____

Additional Questions Additional questions regarding specific user interactions or reactions observed during the testing phase will be asked here to provide deeper insights into individual experiences.

Testing Session Questionnaire

Questions asked regarding the Paris metro network map:

1. What are the names of the stops where you need to change lines?
2. What are the names of the subway lines that the route passes through?
3. How many times does the route come near the river in Paris?
4. How many underground connections does Place d'Italie station have?
5. How many stations do you go through on the first line before switching to another line?
6. What are the names of the stops on the first line (U9) where you can switch to other lines?
7. What is the name of the stop on the second underground line that has the most connections?
8. Which stops on the second underground line are near the tennis courts?
9. What is the name of the stop on the third underground line that has the most connections?
10. Which stops on the third underground line are near the opera house?

Questions asked regarding the Madrid metro network map:

1. What are the names of the stops where you need to change lines?
2. What are the names of the subway lines that the route passes through?
3. How many underground connections does Alonso station have?
4. How many times does the route come close to the river in Madrid?
5. How many stations do you go through on the first line before switching to another line?
6. What are the names of the stops on the second line where you can switch to other lines?
7. Which stops on the second underground line are near the zoo?
8. What is the name of the stop or stops on the third line that have the most connections?
9. What is the name of the stop on the fourth underground line that has the most connections?
10. Which stops on the fourth underground line currently have ongoing construction?

C. CURRICULUM VITAE – GASPAR RAMÔA

EDUCATION

Sept 2018 – July 2020	**Master's degree in computer engineering** (MSc) Universidade da Beira Interior (UBI) Specialisation: computer vision and machine learning Thesis Title: **Artificial Vision for Humans** Supervisor: Professor Dr. Luís Alexandre DOI: 10.13140/RG.2.2.10761.47208
Sept 2015 – July 2018	**Bachelor's degree in computer engineering** (BSc) Universidade da Beira Interior (UBI) **Object recognition for RoboCup@Home Competition** DOI: 10.13140/RG.2.2.19150.08002

WORK EXPERIENCE

July 2025 – Today	**Innovation Lead** at Inventivio GmbH Innovating in assistive tech for inclusive interaction
Nov 2020 – July 2025	**Software developer** at Inventivio GmbH Developing dynamic audio-tactile user interfaces and more
Oct 2020 – Jan 2022	**Co-founder & Software Engineer** at DeepNeuronic Topic: Automated Surveillance Systems.
Sept 2019 – July 2020	**Student research assistant** at SOCIA Lab. (UBI) Topic: Pattern and image analysis

ADDITIONAL EXPERIENCE

Awards	1st prize 2020 Health Cup Competition awarded by the University of Beira Interior and UBIMedical incubator. The award was given to "CovidSight" and "Tox et". October 2020
	1st prize 2020 Hackathon Biomedical World 3.0 Competition, awarded by the University of Beira Interior and UBIMedical incubator. The award was given to "CovidSight" Artificial Intelligence tool for tracking possible infections by Covid-19, which uses temperature control, use of personal protective equipment and social distancing, developed by Vasco Lopes, Bruno Degardin, Nuno Pereira, and Gaspar Ramôa. July 2020
	Best student award relative to the 1st and 2nd year of master's in Computer Science and Engineering – Informatics Department. Academic year of 2018/2019 and 2019/2020.
Conferences & Fairs	IEEE ICARSC 2020, virtual
	INTUITIVE Research School 1, 2021, virtual
	ICCHP-AAATE 2022, Lecco, Italy
	INTUITIVE Research School 2, 2022, Genova, Italy
	PETRA Conference 2023, virtual
	SightCity 2023, Frankfurt, Exhibitor -Inventivio GmbH
	INTUITIVE Research School 3, 2023, Valeta, Malta
	SightCity 2024, Frankfurt, Exhibitor -Inventivio GmbH
	ASSETS (ACM SIGACCESS) 2025, Denver, Colorado

D. AUTHORED PUBLICATIONS

This doctoral work resulted in the following dissertation-related publications:

1. **Classification of 2D refreshable tactile user interfaces**
   Gaspar Ramôa
   Assistive Technology, Accessibility and (e) Inclusion, ICCHP-AAATE, 2022
2. **Developing Dynamic Audio Navigation UIs to Pinpoint Elements in Tactile Graphics**
   Gaspar Ramôa, Vincent Schmidt, Peter König
   Multimodal Technologies and Interaction, 2022
3. **Display and Use of Station Floor Plans on 2D Pin Matrix Displays for Blind and Visually Impaired People**
   Gaspar Ramôa, Omar Moured, Karin Müller, Thorsten Schwarz, Rainer Stiefelhagen
   Proceedings of the 16th International Conference on PErvasive Technologies Related to Assistive Environments. PETRA, 2023
4. **Enabling People with Blindness to Distinguish Lines of Mathematical Charts with Audio-Tactile Graphic Readers**
   Gaspar Ramôa, Omar Moured, Thorsten Schwarz, Karin Müller, Rainer Stiefelhagen
   Proceedings of the 16th International Conference on PErvasive Technologies Related to Assistive Environments. PETRA, 2023
5. **SONOICE! a Sonar–Voice dynamic user interface for assisting individuals with blindness and visual impairment in pinpointing elements in 2D tactile readers**
   Gaspar Ramôa, Vincent Schmidt, Thorsten Schwarz, Rainer Stiefelhagen, Peter König
   Frontiers in Rehabilitation Sciences, 2024

The following publications were authored by Gaspar Ramôa but are not directly related to this dissertation research:

1. **Real-Time 3D door detection and classification on a low-power device**
   Gaspar Ramôa, Luís Alexandre, Sandra Mogo
   2020 IEEE International Conference on Autonomous Robot Systems and Competitions (ICARSC), 2020
2. **Real-time 2d–3d door detection and state classification on a low-power device**
   Gaspar Ramôa, Vasco Lopes, Luís Alexandre, Sandra Mogo
   SN Applied Sciences, 2021