Charting Beyond Sight with DataStory: Sensory Substitution and Storytelling in Visual Literacy Education for Visually Impaired Children

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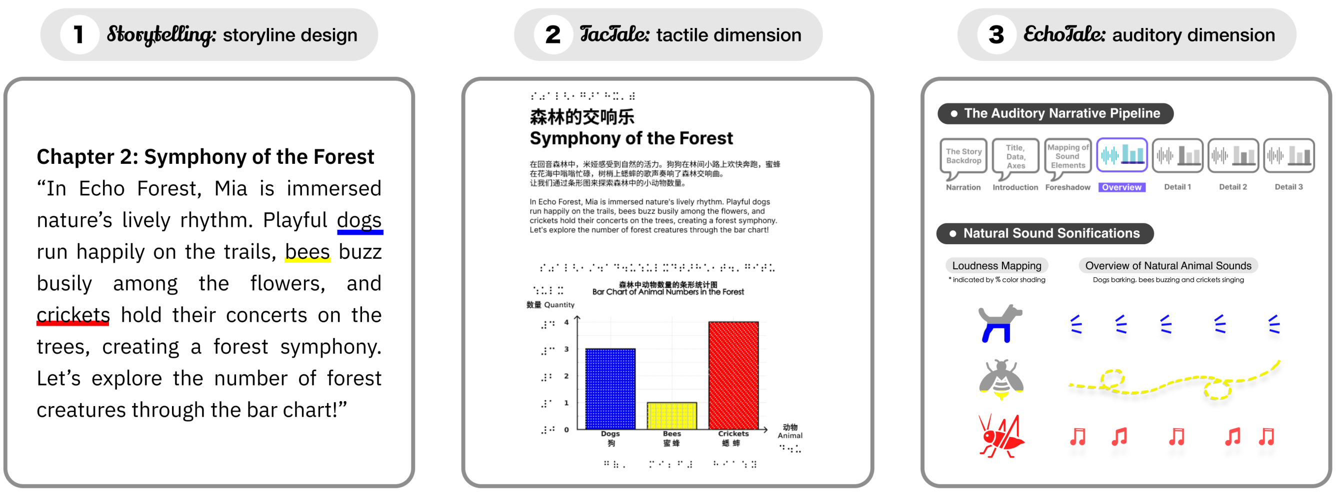

Figure 1: DataStory's Multisensory Learning Strategy: (1) Storytelling that embeds learning within engaging narratives; (2) TacTale, a storybook featuring tactile visualizations; and (3) EchoTale, audio narratives blended with natural soundscapes for data sonifications.

ABSTRACT

Visualizations transform raw data into accessible insights. However, they often exclude the visually impaired community. Despite tools like alt-texts and screen readers for translating visual information, visual literacy remains a fundamental barrier to interpreting visual data. Standard visual literacy education is less accessible to visually impaired learners. Our study explores visualization education through alternative sensory channels for visually impaired students. This work has three main contributions: examining educational practices for visually impaired students at a special education school; defining design requirements focused on sensory substitution; and developing a storytelling-based assistive learning prototype. The final design, DataStory, is a tactile storybook with embedded visualizations and sonified data narratives. To evaluate its feasibility, we conducted a pilot study with proxy students and a special education teacher. The paper concludes with a discussion on limitations and future directions in assistive visualization education, promoting further research into equitable educational tools for visually impaired children.

CCS CONCEPTS

• **Human-centered computing → Accessibility design and evaluation methods**; **Visualization design and evaluation methods**.

KEYWORDS

Assistive learning technologies, Visually impaired education, Sensory substitution, Storytelling

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1 INTRODUCTION

Data visualizations, such as charts and graphs, are integral to transforming data in their raw forms into actionable insights across various fields [2, 6, 13, 19, 25]. The increasingly widespread use of visualizations highlights the importance of developing skills to interpret them effectively. Such cognitive abilities involved in processing information from data visualizations are referred to as visual literacy, which encompasses both encoding data into visualizations and decoding information from visualizations [22].

Educational systems play a crucial role in developing visual literacy, a skill traditionally integrated into the standard K-12 mathematics curriculum [18]. As part of their education, students learn about various chart types, such as line charts, bar charts, and scatter plots, along with key elements of visualizations including titles, axes, and data attributes. The curriculum is designed to foster essential visual literacy skills, focusing on tasks like identifying patterns, discerning trends, and interpreting data clusters.

However, the visually impaired individuals, comprising 217 million of the global population [3], often find these visual aids inaccessible. Despite gradual developments in accessibility tools like screen readers and alternative texts, barriers remain for the visually impaired community in accessing and interpreting visualizations, and in engaging in visually-driven discussions [8]. This inaccessibility hinders the opportunities and equity of the visually impaired community. As a result, they may struggle to make informed decisions or engage in meaningful discussions. An example is the "flattening the curve" analogy used during the COVID-19 pandemic [23]. While intuitive to sighted individuals, understanding these concepts requires two dimensions of information decoding: first, access to the visual information; and second, possession of the visual literacy to understand what a "curve" is and what it means to "flatten" it.

Therefore, while we continue to develop assistive tools that strengthen alternative channels for visual information access, it is also paramount to equip the visually impaired community with the necessary skills and visual literacy to understand visual concepts. While sighted children are introduced to data visualizations early in their education, visually impaired children should not be left behind. How can we improve current visualization learning for this minority population? Truly accessible visualization requires a paradigm shift that values the experiences of visually impaired individuals from the beginning of the design process, rather than retrofitting solutions onto existing visual frameworks [8]. This is why it is essential to investigate current practices, discern opportunities, and create solutions that cater to their learning needs.

This project explores assistive visual literacy education in a three-stage manner: Investigating the current teaching and learning methods for visually impaired children (discover); Drawing insights from observations and dialogues to formulate design requirements and make key design decisions (define); then creating and evaluating innovative assistive design solutions (develop). In this work, we present a user-centred approach to design assistive learning tools for visually impaired children in special education schools in China. After conducting a field study at a special education facility, we developed the *DataStory* prototype, which includes a tactile storybook component called *TacTale* to convey visualizations through touch, and a data sonification component called *EchoTale* that maps data dimensions to audio dimensions.

2 RELATED WORK

Storytelling in Visualization and Education: Data storytelling is an emerging technique in visualization that offers significant potential in education. The use of narrative elements in data presentation can engage students, fostering visualization literacy through playful and curiosity-driven approaches. This approach is especially relevant in educational settings, where storytelling can be a powerful tool to capture students' attention and make complex data more comprehensible. For example, Dietz et al. [9] developed StoryCoder, a voice-guided application teaching computational thinking to children aged 5-8 through storytelling. They demonstrated storytelling's effectiveness in a learning context for concepts like sequences and variables. In their subsequent work, they presented Visual StoryCoder [10], where they combined voice guidance with a block-like graphical interface for storytelling. Their work highlighted the synergy of storytelling with visual and auditory elements for education. Moreover, storytelling is also used in more professional learning contexts. For instance, Martinez-Maldonado et al. [24] used a layered storytelling approach for for visualizing complex data in medical training and simulations. More specifically, storytelling has also been used for the visually impaired. Chopra and Gupta developed StoryBox [7], a multi-modal storytelling platform for visually impaired children. Their design utilizes audio narration along with sensor-enabled tactile figurines.

Sensory Substitution Techniques: Visual cues in data representation often exclude those with visual impairments. Recognizing this, research by Wang et al. [29] highlights the necessity for accessible visualization using sensory substitution. Auditory and tactile channels have been recognized as effective alternatives in related works. *Data Sonification* uses non-speech audio to convey information and has been studied extensively in previous works [1, 4, 5, 11, 12, 14–17, 20, 21, 26–30]. For instance, Hoque et al. examined several sonification studies from five distinct dimensions, namely audio type, sonic mappings, play order, information seeking and application domain. Designs such as iSonic [30] and the Web Sonification Sandbox [20] revealed the potential for sonification to enable data exploration for visually impaired users. Fewer works investigate the classroom integration of sonification and accessible visualization. Tomlinson et al. [28] provided case studies of auditory graphing software in classroom settings, offering insights into the practical challenges and pedagogical opportunities. Very few studies explore using sonification to enable the learning of visual literacy-related concepts for visually impaired children. On the other hand, *tactile feedback* provides additional avenues for data representation. For instance, Fan et al. [12], and Goncu and Marriott [15] explored how tactile and haptic interfaces can convey data-driven graphs. These studies demonstrate the potential of tactile and haptic feedback to enrich data exploration.

These existing solutions, while diverse, do not specifically target visual literacy learning for visually impaired children. This paper addresses this gap by proposing a solution that is not only grounded in user insights but also aligns effectively with the current educational practices for this demographic in China. Our strategy focuses on crafting an accessible tool for visual literacy learning.

3 RESEARCH AND DESIGN PROCESS

The overarching research design corresponds with the three stages stated in our introduction: *discover*, *define*, and *develop*. The sequential flow of these stages forms the backbone of our methodology. This section provides details on the discover and define phases in seeking user insights and deriving design decisions.

3.1 Discover Current Practices via Fieldwork

We conducted a field study at a local special education school in China to gain first-hand insights into current educational strategies for visually impaired students. This involved observing both the school's environment and the interaction between students and teachers during a sixth-grade mathematics class comprising of six students and one teacher. To engage in more in-depth conversations, we carried out a semi-structured interview with the math teacher, covering topics such as administration, curriculum, teaching materials, strategies, and evaluation methods. The interview lasted for about two hours, which was audio-recorded and later transcribed for analysis. This study was approved by the university ethics committee.

3.2 Define Personas and Design Considerations

Based on the qualitative data collected during our fieldwork, we developed separate user personas for students and teachers, the main stakeholders in our design.

Student Personas: Our student personas include both blind and low-vision individuals, with 1/6 being low-vision and 5/6 blind. Blind students primarily use braille, while low-vision students rely on visual textbooks, sometimes enhanced with magnification aids. A common challenge for both groups is understanding abstract concepts, particularly in visualization and geometry, necessitating tailored approaches to meet their diverse needs.

Teacher Persona: The teachers combine traditional curriculum-based methods with real-world scenario teaching, using materials like braille textbooks and custom aids made by materials like magnets and whiteboards. A significant challenge is creating effective, time-efficient teaching aids, as custom props are often time-consuming to prepare. Digital devices and screen readers are not currently used as part of the curriculum.

Utilizing these personas, we formulated a set of design considerations (DCs) that mirror the user needs and comply with the theoretical principles in China's educational guidelines [1]. This approach guarantees that our DCs meet the specific needs of our user personas and are in line with fundamental special education principles. The established personas and corresponding DCs are illustrated in Figure 2.

The DCs together with the user personas helped us develop informed design decisions. First, we focused on multisensory learning through sensory substitution, specifically using data sonification to harness the pattern recognition capability of the auditory system (DC1). Second, we integrated tactile graphics into the visualizations, utilizing familiar tools like braille paper and styluses to enhance teaching effectiveness (DC2). For engagement, we incorporated storytelling elements into our design (DC3). Finally, we addressed the needs of both blind and low-vision students by creating hybrid designs that combine braille with enlarged visuals (DC4). These decisions lead to *DataStory*, a comprehensive solution tailored to the specific learning requirements of visually impaired students.

4 DESIGN OF *DATASTORY*

There are three key design elements giving rise to DataStory: storyline design, visualization design, and audio design. Together, these elements form two integrated entities: TacTale, a tactile storybook for touch engagement, and EchoTale, providing a narrated and sonified experience for auditory interaction. The following subsections detail each of these design elements and their integration to the complete DataStory solution.

4.1 Storyline Design

The storybook's backbone is an adventure-themed narrative designed to introduce data visualization concepts within an engaging story. Aimed at children under 12, the storyline is simple, captivating, and interwoven with data and visualization elements. It features a nature-themed setting with a young explorer, Mia, as the protagonist. The story consists of a foreword, three main chapters, and a conclusion, each chapter integrating data concepts into Mia's adventures. Figure 3 presents the scripts of the story. While the text excerpts are in English for uniformity, the actual design is trilingual, incorporating Braille, Mandarin Chinese, and English considering our user base in China. This approach ensures inclusivity and accessibility for a diverse young audience.

4.2 Visualization Design

To align with the storyline of each chapter, we designed corresponding visualizations (Figure 4), specifically line charts, bar charts, and scatter plots. These were chosen for their common use in elementary curricula and effectiveness in discerning trends, facilitating comparisons, and pinpointing outliers. Designed to be accessible for both blind and low-vision students, these visualizations combine tactile features with distinct visual elements. Blind students can use raised lines and dots for tactile interpretation, while low-vision students benefit from bright colors and enlarged features to aid in visual comprehension. Please refer to Appendix A.1 for a detailed view of the chart anatomy.

4.3 Audio Design

In developing the auditory component, we were inspired by two studies: the Susurrus project [17], which promotes natural sound sonification, and Siu et al.'s research [27] advocating for accessible data visualization through audio narratives. Our goal was to blend the familiarity of natural sounds with the clarity provided by narrative elements and combine the merits of both.

For our natural sound sonification, we compiled a database of river, animal, and insect sounds from the Youtube Audio Library.

[1]http://www.moe.gov.cn

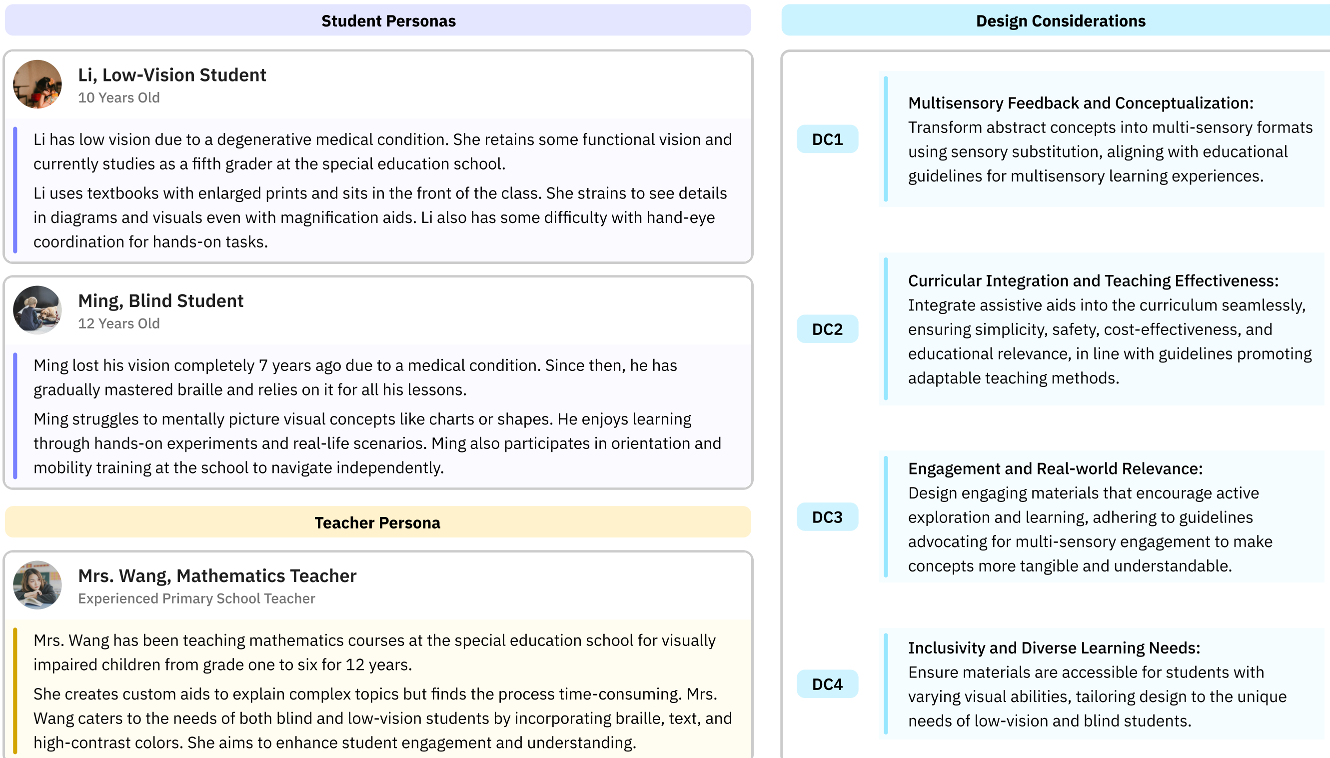

Figure 2: Summary of user personas and the derived design considerations

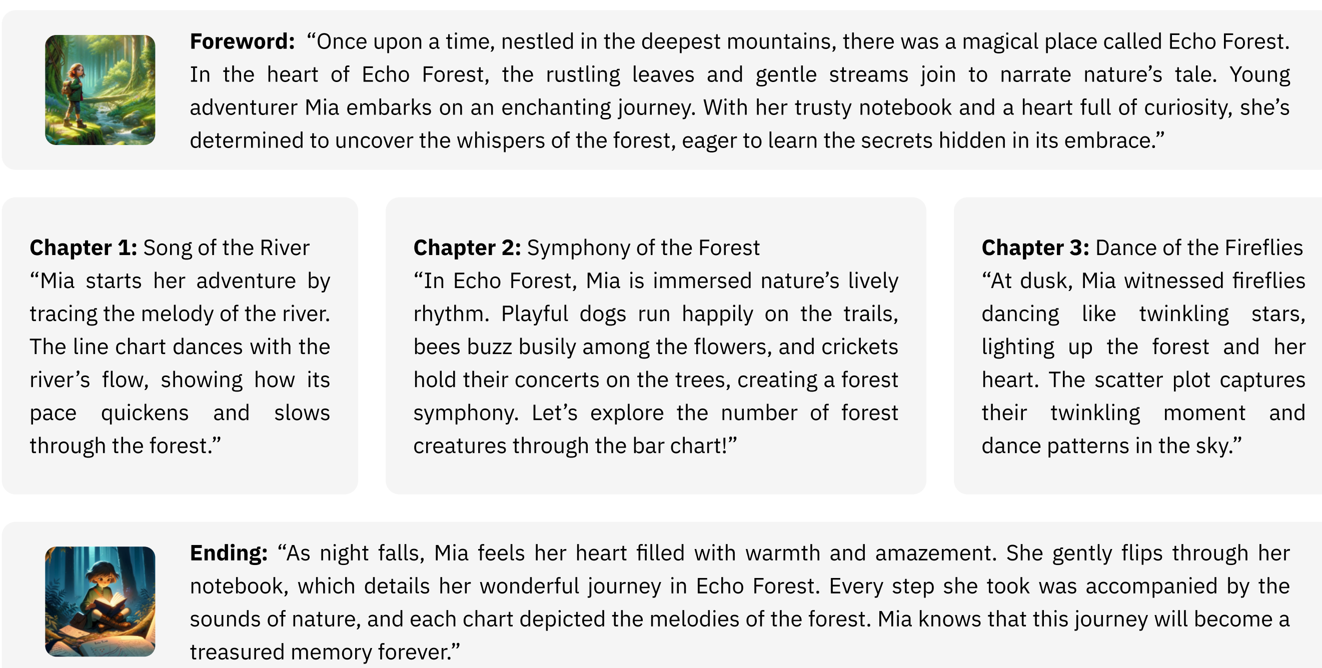

Figure 3: Scripts of the storyline, composed of a foreword of the story context, three main chapters, and an ending.

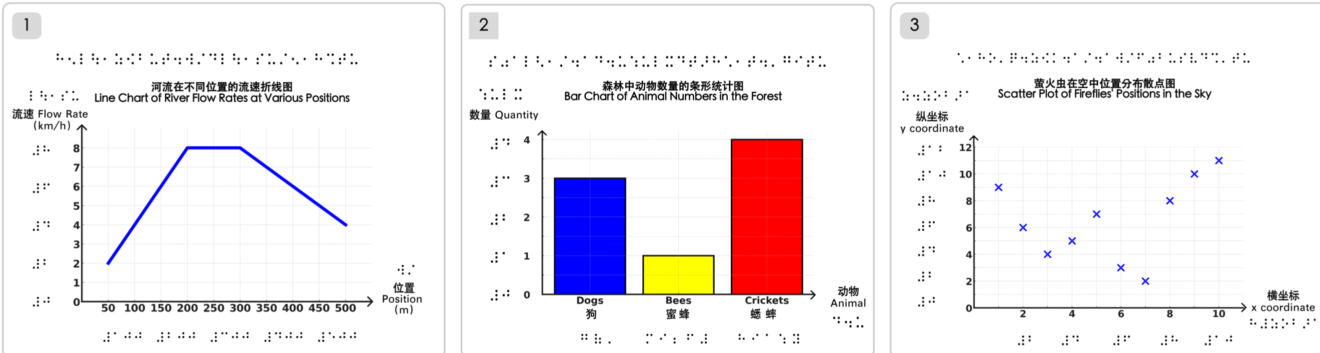

Figure 4: The three designed visualizations: (1) A line chart for river flow rates. (2) A bar chart for quantities of forest animals. (3) A scatter plot for firefly positions. All made inclusive with Braille, bright colors, and enlarged fonts.

These copyright-free sounds were chosen for their relevance. Following the Susurrus project's [17] approach, we applied positive-polarity loudness mappings, adjusting sound intensity with data values using Python and Pydub (Appendix A.2). The loudness mapping technique, which scales the output volume of the audio based on the data input, is designed to be adaptable and technically generalizable across different data types. For the data narratives, we used Google's text-to-speech technology in Python, creating separate audio files for background and data narratives.

4.4 DataStory Experience: TacTale & EchoTale

The design components come together in a cohesive solution that combines tactile (TacTale) and auditory (EchoTale) experiences. Together they provide a holistic multi-sensory DataStory learning experience (Figure 5).

TacTale refers to the interactive tactile storybook featuring text and tactile graphics (Figure 6), enabling exploration through touch. The physical rendition of TacTale was crafted from A4-sized kraft papers, which are materials traditionally used for Braille writing in the school. Printed elements such as titles, text, and graphics were first applied to the pages. Subsequently, braille and raised tactile features were added using a standard braille stylus. Note that the braille used in this prototype was Mainland Chinese Braille considering our specific group of users.

EchoTale enriches this with auditory narratives, creating a soundscape that complements the tactile feedback. It begins with ***Narration***, setting the story's context and drawing listeners into the narrative. Following this, the ***Introduction*** outlines the visualization details, such as the chart title and data attributes, preparing listeners for data exploration. The ***Foreshadow*** segment introduces the acoustic elements and sonification mapping technique to be used. Next, the ***Overview*** provides an auditory representation of the entire dataset, giving listeners a sense of overall trends and patterns. Finally, the ***Detail*** segment delves into specific data aspects, focusing on trends, individual points, and outliers, guiding listeners through detailed information-seeking tasks. For a more straightforward understanding of the DataStory experience, please refer to Appendix A.4 while listening to the video demonstration.

5 PRELIMINARY EVALUATION

5.1 Natural Sounds versus Multitones

The decision to use natural sound elements for sonification was validated by comparing it with traditional multitones, which varies in pitch, loudness, and timbre to represent data. We generated equivalent multitone stimuli in Python with the Sonipy tool [2].

We conducted a within-subject study with 9 sighted and blindfolded elementary school students (grades five-six) as proxies, consisting of 5 females, 4 males. The experiment consisted of six conditions (3 chapters $\times$ 2 sonification techniques) to gauge engagement, comprehension, and preference. The participants rated engagement and comprehension on a 0-10 scale and chose their preferred sonification method. It is important to acknowledge that all three metrics here were regarded as self-reported subjective measures, rather than direct measurements of learning outcomes. The results (see charts in Appendix A.3) showed higher engagement with natural sounds (7.2 ± 1.8) than multitones (6.8 ± 1.9), although comprehension was indifferent for both methods. Most participants (6 out of 9) preferred natural sonification, with 2 having no preference and only 1 favoring multitones. These findings led us to select natural sound sonification for our final design.

5.2 Qualitative Feedback on Feasibility

We obtained qualitative feedback on the feasibility of the DataStory solution through a 1.5-hour interview session with the mathematics teacher, who interacted with our prototype and offered insights.

The teacher appreciated the imaginative quality of DataStory's narratives, appreciating their dual role in educating and entertaining young learners. However, they noted the challenge of weaving ***complex data concepts*** into simple, engaging stories that suit young students' cognitive abilities and attention spans. The teacher suggested integrating data concepts into the narrative through metaphors, analogies, and character-driven scenarios for relatability and understanding. Another key aspect highlighted was DataStory's potential to encourage ***independent learning***, envisioned as a tool for self-guided exploration, critical thinking, and as a take-home resource to extend learning beyond the classroom. The

[2]https://github.com/lockepatton/sonipy

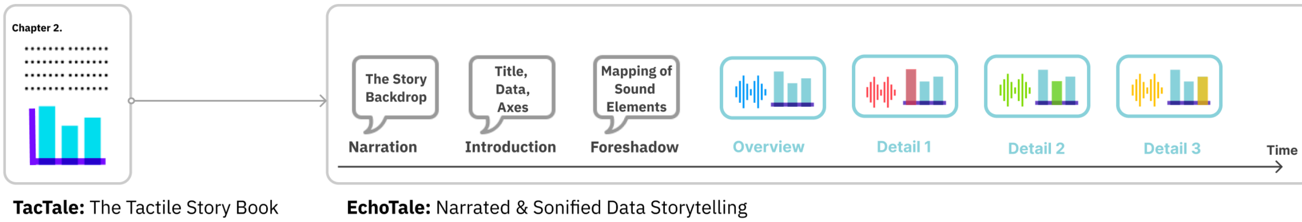

Figure 5: The DataStory experience, integrating tactile and auditory elements to provide a multi-sensory educational journey.

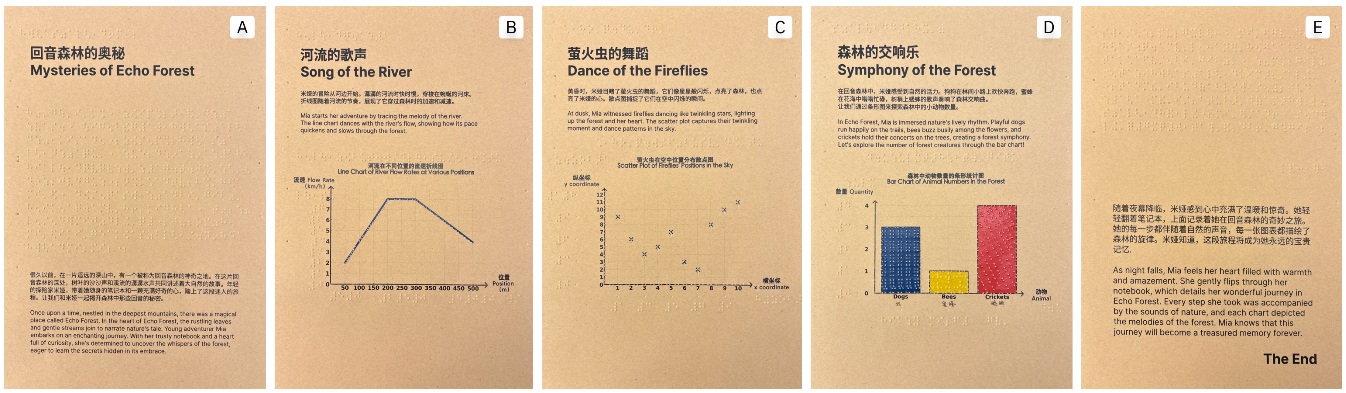

Figure 6: The TacTale prototype pages.

teacher commented that such independence is crucial for building confidence for students with visual impairments. Regarding sonification, the teacher proposed ***integrating both multitone and natural soundscapes*** to cater to varied auditory preferences, enhancing the learning experience. Additionally, the teacher emphasized the need for an automated sonification system to streamline the preparation of teaching materials and ensure consistency in quality. Overall, the qualitative feedback affirmed DataStory's potential and provided direction for refining the solution to better meet the educational needs of visually impaired students.

6 DISCUSSION AND FUTURE WORK

The DataStory design offers an accessible approach to teaching data visualization to visually impaired students. This section discusses its implications, limitations, and potential future research directions.

Integration of Auditory and Tactile Dimensions. The integration of auditory and tactile components can be further explored. In our study, we experimented with portable audio modules and NFC tags for embedding audio into the story pages. The modules offer an independent audio experience but pose physical integration challenges due to their size, while NFC tags ensure subtler integration but require secondary devices like smartphones, potentially limiting accessibility. Future work will explore advanced audio playback technologies integrated directly into tactile storybook pages, maintaining physical integrity and enhancing user experience.

Direct Involvement of Visually-Impaired Individuals in Co-Design. While proxy participants offer valuable insights, they cannot wholly replicate the unique experiences and intricate needs of the visually impaired community. Future design iterations should involve visually impaired individuals directly in the co-design process. Their involvement throughout design stages ensures genuinely user-centered solutions. In-situ validation in real educational settings will assess the tools' practicality and adaptability.

Expanding the Scope of Accessible Visualization Types. Expanding beyond basic charts, future work should determine the extent to which the techniques developed for basic charts can be generalized to more complex visualizations such as network diagrams and heat maps. It is essential to assess whether methods like sonification and tactile feedback, successful in conveying simple data plots, can be effectively extended to represent more intricate data structures. This investigation requires a detailed examination of the distinct features specific to each type of visualization and the creation of customized methods to translate these into accessible, non-visual formats.

7 CONCLUSION

In this project, we aimed to enhance the visual literacy education of visually impaired students through storytelling, sensory substitution and audio narrative-based learning. We began by gathering insights through fieldwork and interviews at a local special education school. The requirements and needs of the users were carefully considered in the development of our final solution, DataStory. DataStory comprises two components: TacTale, a tactile storybook that includes visualizations, and EchoTale, which provides audio narratives of the story and visual literacy concepts. The feasibility of this design was validated with proxy students who are sighted and a special education teacher. Future work will involve a deeper co-design process with visually impaired students, refining the integration of auditory and tactile elements, and exploring a wider range of visualization types. Ultimately, this research offers a novel approach to teaching visualization literacy to visually impaired students, aiming for an inclusive educational environment where all students can appreciate the power and beauty of data visualizations.

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A APPENDIX

A.1 Anatomy of the Accessible Visualization

In developing accessible visualizations, several key design considerations are employed to enhance the accessibility of visualizations. Specific features are highlighted in blue for design considerations and in pink for key visualization concepts.

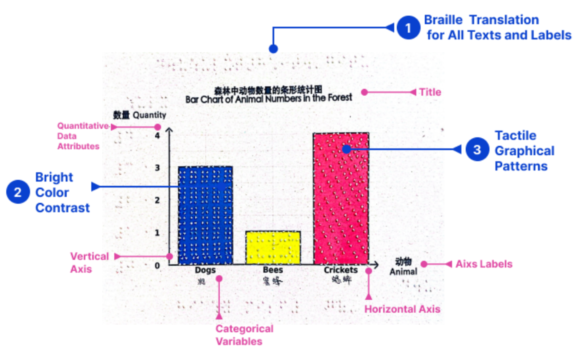

Figure 7: Accessible design features: (1) Braille for texts and labels; (2) Bright color contrast for distinguishing between different data sets; and (3) Tactile patterns allow users to feel the data through touch.

A.2 Pipeline for Data Sonification Mapping

The pipeline below showcases the workflow of mapping data to its auditory dimension as part of the sonification design.

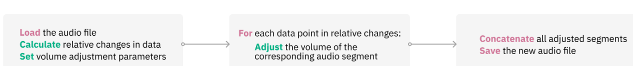

Figure 8: Illustration of the auditory intensity mapping flow in sonification design.

A.3 Evaluation of Natural Sounds vs. Multitones

The evaluation results comparing natural sonifications with multitones are summarized below.

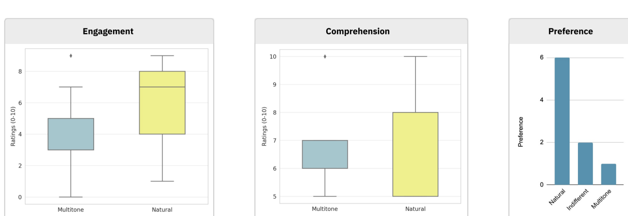

Figure 9: Summary of user evaluation results on engagement, comprehension, and preference.

A.4 Demonstration of the DataStory Experience

This section provides an overview of complete the DataStory experience using chapter one as an example, showcasing the interplay between TacTale and EchoTale.

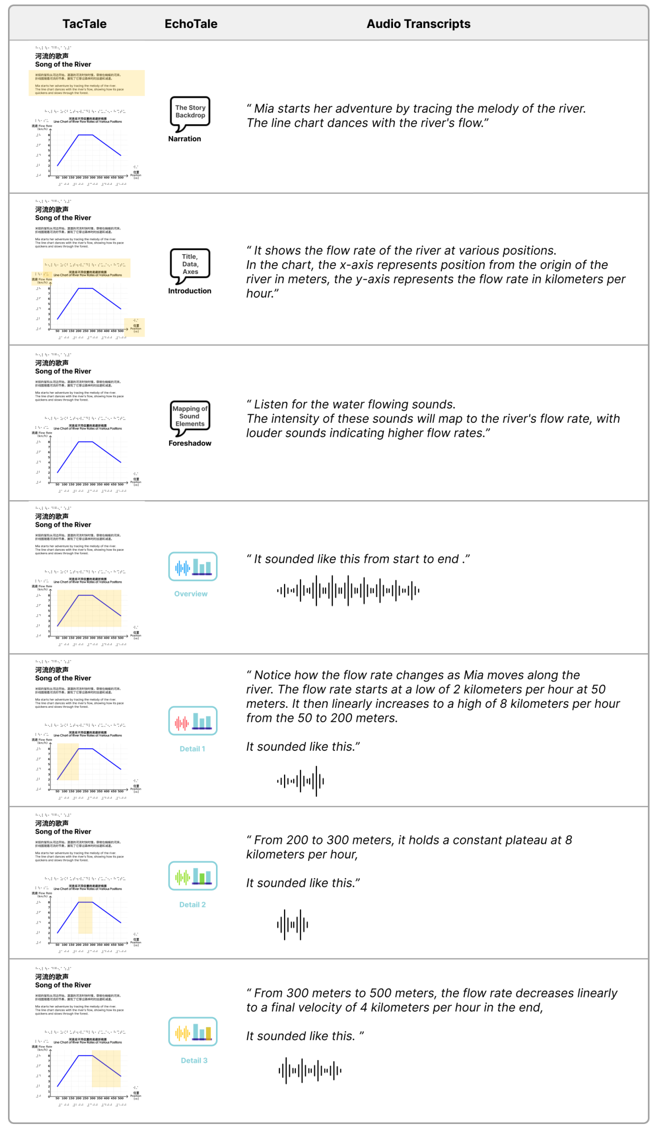

Figure 10: A step-by-step demonstration of the DataStory experience: The left column displays TacTale's tactile features, the middle column outlines the stages of data narrative, and the right column presents the auditory transcripts, including story narration and data sonification.