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Research on Interactive Design Practice Based on Barrier-Free Perspective

-- Taking Braille Reading and Writing Learning Machine as an Example

Chunhao Zheng

Northeast Petroleum University, Daqing Heilongjiang, 163000, China

Abstract: Within the policy framework of China's active promotion of barrier-free environment construction—highlighted by documents like the 14th Five-Year Plan for Barrier-Free Environment Construction—the significance of information accessibility for visually impaired individuals has grown exponentially. This study employs scientific methodologies, including user surveys and product iteration cycles, to address the challenges faced by visually impaired learners in Braille education. By innovatively integrating the concept of multimodal interactive design into Braille educational contexts, the research focuses on developing Braille reading and writing learning machines to bridge existing gaps in design scholarship. This initiative holds substantial social value in enhancing educational quality for visually impaired populations and advancing societal equity.

Keywords: Barrier-free Design; Product Design; Interactive Design; Braille Reading and Writing Learning Machine; Blind Children's Learning.

1. Research Background and Significance

Social civilization advancements highlight barrier-free environment construction, with information accessibility critical for visually impaired individuals' social integration and knowledge acquisition. The 2021 14th Five-Year Plan emphasizes improving such infrastructure, yet China's 17.32 million visually impaired population (2022 China Blind Association data) faces a Braille literacy rate below 10%. Traditional teaching aids like convex dot boards suffer from limited interactivity: reliance on tactile-only learning and lack of real-time feedback hinder self-assessment and timely guidance, reducing efficiency and motivation.

This study aims to establish a "user-centered barrier-free interaction design methodology," addressing gaps in Braille educational equipment research. By analyzing user needs/pain points and integrating advanced technologies, it seeks to develop an efficient Braille learning tool, enhancing accessibility for visually impaired learners, elevating their education and quality of life, and advancing social equity.

2. Theoretical Origin and Architecture of Accessible Interaction Design

2.1. The Evolution and Core Meaning of Barrier-Free Design

Accessible design, as an important paradigm in the field of modern design, emerged in the mid-20th century. At that time, the promulgation of the Universal Declaration of Human Rights set off a wave of pursuit of human rights and equality around the world. This concept gradually penetrated from the field of architecture to many fields such as product design and information interaction.[1]. Unlike traditional design, barrier-free design adheres to the forward-looking principle of universal design, requiring designers to systematically consider the diverse needs of groups with different abilities in the early stages of product design, rather than making local, remedial modifications afterwards. Its core concept focuses on inclusiveness and fairness. This is not only reflected in the deep concern for the special needs of disabled groups, such as the blind's reliance on tactile and auditory information interaction, and the requirements of people with physical disabilities for ease of operation and spatial accessibility, but also extends to the full foresight of the obstacles that the elderly and children may encounter in specific scenarios. Taking the design of subway stations as an example, the laying of blind paths, the setting up of voice announcement systems, and the provision of barrier-free elevators are all specific applications of barrier-free design in public spaces, ensuring that everyone, regardless of their physical condition or ability level, can participate equally in social life and share the benefits brought by scientific and technological progress.

2.2. Theoretical Analysis of Interaction Design Principles

Interaction design focuses on creating meaningful engagement between users and products/systems/ environments. In barrier-free design, usability, accessibility, and user experience are core principles. Usability demands high learnability and ease of use to help users efficiently complete tasks. Accessibility emphasizes open, inclusive design for all users, requiring designers to account for perceptual, motor, and cognitive differences—e.g., equipping Braille learning machines with voice navigation and tactile feedback to enable non-visual interaction.

User experience encompasses users' overall feelings during use, including emotions, attitudes, and satisfaction. Effective barrier-free design must address functional needs while delivering positive emotional experiences, enhancing user identification with the product and fostering long-term engagement.

2.3. Theoretical Analysis of The Integration of Accessibility and Interaction Design

The deep integration of barrier-free design and interactive design has a deep foundation in cognitive psychology and social learning theory. Cognitive psychology research shows that humans obtain information through multiple sensory channels, and different senses cooperate and complement each other in the process of information processing. Therefore, when designing interactive products, fully mobilizing multiple sensory channels can significantly improve the efficiency and accuracy of information transmission. For the visually impaired, touch and hearing are their main ways to obtain information. The design of the Braille reading and writing learning machine is based on this theory. Through a carefully designed tactile feedback mechanism, it helps users identify Braille symbols; with the help of clear and accurate voice prompts, it guides users to operate. In addition, social learning theory emphasizes the important influence of the environment on individual learning. Barrier-free interactive design provides the visually impaired with rich learning resources and convenient learning tools by creating a supportive learning environment, helping them to learn Braille knowledge more effectively and improve their learning ability.

3. Visually Impaired Needs and Braille Literacy Analysis

3.1. Macro Challenges: Social Integration and Information Access Gaps

The visually impaired group exhibits unique characteristics in perception, movement and cognition. In the perception dimension, due to the lack of visual function, the blind mainly relies on touch, hearing and smell to obtain external information. Touch plays a core role in Braille reading and writing. By touching the raised Braille dots, the blind can recognize words and symbols; hearing plays an important role in daily life, helping the blind to locate, identify environmental sounds, and obtain key information.

At the social level, due to the lack of vision, the visually impaired mainly rely on touch and hearing to interact with the outside world. In terms of text information processing, although traditional Braille provides a basic way of reading and writing for the visually impaired, the touch reading speed is slow, and long-term use can easily lead to hand fatigue, which greatly limits the efficiency of information acquisition. The current voice prompt system lacks personalized customization, and the sound recognition is low in noisy environments, making it difficult for the visually impaired to accurately receive information. Although auxiliary tools such as guide dogs and blind sticks help the visually impaired to move to a certain extent, the complex traffic conditions and layout of public facilities increase the difficulty and risk of their travel, limit their range of movement and social activities, and hinder the process of the visually impaired into society.

Table 1. Analysis of Visual Perception in Blind Children

Classification of sensory perception for blind children	Perceptual characteristics of blind children	Product demand for blind children's reading and writing learning machines
Touch	Due to long-term reliance on touch (such as reading Braille), blind children usually have higher tactile sensitivity in their fingertips than normal children, and can quickly distinguish tiny differences (such as a 0.1mm error in Braille height).	For blind children, the height of the Braille dots (about 0.6-0.9mm according to international standards) and the spacing (about 2.5mm) must meet the standards to adapt to the weaker fingertip sensitivity of children and avoid tactile fatigue. Skin-friendly materials should be used to reduce the friction caused by long-term touch, and they should also be wear-resistant and anti-fouling.
Hearing	Due to the lack of visual function, blind children have significantly enhanced compensatory hearing development, and their ability to locate sound sources and process sound information is stronger than that of normal children.	For blind children, it is necessary to ensure the clarity and flexibility of voice interaction, use a high-fidelity children's voice library to avoid a mechanical feel, and support multi-level adjustment of speech speed.

3.2. Meso-level: Braille Reading and Writing Education Ecology and Equipment Adaptation Dilemma

Although Braille is an important tool for the visually impaired to acquire knowledge, the current learning of Braille reading and writing faces many severe challenges. First, the Braille symbol system is complex and difficult to learn, and learners need to spend a lot of time and energy to memorize and practice. According to statistics from relevant education departments, the average time for visually impaired students to learn Braille is 30% - 50% longer than that for ordinary students to learn Chinese characters. From the perspective of educational ecology, the abstractness and complexity of the Braille symbol system determine that visually impaired students need to spend more time learning Braille.

However, the current distribution of Braille teaching resources is seriously uneven in terms of region. Visually impaired students in remote areas have fewer opportunities to access high-quality educational resources and mainly rely on face-to-face guidance from teachers. The quantity and quality of online teaching resources need to be improved. In terms of equipment adaptation, the operation process of traditional Braille writing tools is cumbersome, which reduces writing efficiency; Braille reading devices on the market have single functions and are expensive, which is beyond the affordability of ordinary visually impaired families. In the process of digital transformation of Braille electronic texts, due to the lack of unified format standards, garbled characters and loss often occur during format conversion and data transmission, which restricts the informatization development of Braille education.

3.3. Micro-level: Difficulties in Daily Interaction and Reading and Writing Operations for Visually Impaired Individuals

In daily life, visually impaired individuals face challenges like insufficient tactile feedback on device interfaces and delayed voice interaction—e.g., mobile phones with cumbersome barrier-free functions and inconsistent app accessibility. For Braille reading/writing, issues include unstable paper quality (blurred embossing), easily worn pen tips (irregular dots), and lagging Braille book updates, hindering knowledge access. These micro-level problems directly impact daily experience and learning efficiency.

Research on Braille learning machine interaction design from a barrier-free perspective is urgently needed. By integrating innovative design and technology, it aims to overcome traditional Braille limitations, creating a more efficient, personalized interactive system to improve visually impaired individuals' lives and advance social equity. The study will also offer new approaches for barrier-free design theory and practice, driving disciplinary development.

4. Practical Strategies for Interactive Design of Braille Reading and Writing Learning Machines

4.1. Project Background and Objectives

In today's era of exponential development of science and technology, educational equity and personalized education have become the core issues of multidisciplinary cross-study such as pedagogy and educational technology. This project precisely anchors the special and urgently needed sub-field of education for visually impaired children, aiming to develop an innovative intelligent Braille reading and writing learning machine through cutting-edge technology integration and innovative design. The project deeply integrates the child-friendly design theory in human-computer interaction and the concept of precise learning empowerment in educational psychology, and is committed to building an efficient and immersive new path for knowledge acquisition for visually impaired children. On the other hand, domestic digital Braille devices currently have defects in product interaction design and cannot effectively teach blind children. Other devices are expensive. For example, the Focus 14 Blue dynamic dot display produced by Freedom Scientific in the United States has a market price of about RMB 23,000, which is far beyond the affordability of ordinary families.

Therefore, the goal of this project is to design an intelligent Braille reading and writing learning machine with child-friendly interactive design and precise learning empowerment, to lower the economic threshold for visually impaired children to obtain advanced learning tools, and to promote the fair distribution and popularization of special education resources.

4.2. Analysis of Pain Points in the Early Stage of the Project

Blind children face the dilemma of low efficiency and quality in Braille learning. Traditional educational tools such as paper Braille boards and Braille pens only support one-way input, leaving blind children unable to immediately detect writing errors during practice and requiring manual inspection and feedback from teachers, with an error correction cycle typically exceeding 24 hours. This leads to incorrect movements forming muscle memory, necessitating extra time for subsequent correction. Data shows that 65% of blind children struggle to complete standardized practice volumes, and there is even a phenomenon of "zero-guidance" self-study in remote areas. Meanwhile, current Braille primary school mathematics textbooks still follow the 2003 curriculum standards, failing to meet the new curriculum standards' requirements for cultivating problem-solving skills, resulting in blind children taking an average of 2.5 years to master basic Braille reading and writing—far longer than sighted children's time to learn letters. Long-term reliance on inefficient training models also leads to degeneration of tactile sensitivity: neurological studies indicate that the activity of the tactile cortex in the fingertips of blind children using traditional teaching aids decreases by 3.2% annually, creating a vicious cycle of "inefficient learning—ability degeneration—opportunity deprivation."

Current Braille reading and writing products suffer from inadequate interaction design and functional defects. During core use, tactile input and auditory feedback are severely disjointed: dynamic dot display response delays cause voice prompts to lag behind touch, making it difficult for users to establish tactile-auditory associations. The lack of a physical guidance mechanism leads to high accidental touch rates in complex interfaces, while vague "error" prompts lacking specific guidance force learners to rely on trial and error. Additionally, designs overlook children's behavioral characteristics: key triggering forces exceed children's hand strength thresholds, and interaction lacks progressive guidance, making it difficult for young users to independently complete basic operations. This transforms the virtuous cycle of "exploration—practice—feedback" into a negative experience of "frustration—abandonment," seriously undermining the sustainability of Braille education[2]

Existing device designs have long ignored the unique behavioral patterns and psychological needs of blind children, creating a deep divide between technological tools and users. Behavioral studies show that 72% of blind children experience reduced learning motivation due to the lack of immediate positive incentives (such as point rewards and dynamic sound effects), with an average daily effective learning time of less than 1.2 hours. More seriously, the proliferation of pure voice devices has caused "compensatory degeneration of tactile abilities," forming a vicious cycle of "technology dependence—ability atrophy—deeper dependence." At the operational level, blind children exhibit anxiety reactions to unexpected voice prompts, often repeatedly touching physical buttons to confirm operation status, prolonging task completion time and increasing cognitive pressure. These design flaws not only reduce learning efficiency but also risk triggering psychological resistance, ultimately leading users to abandon device use.

4.3. Analysis of Project Design Strategy

In order to improve the braille learning experience of blind children, based on the above research, this study takes the interactive design experience theory as the theoretical guidance. Taking three typical pain points as the main research objects, the relevant design strategies of braille reading and writing equipment are discussed and studied, and the following conclusions are drawn. Create an "instant response" touch-hearing linkage system.

Table 2. Analysis of Braille reading and writing equipment

product	Description	Features
Traditional Braille Teaching Writing Board	Widely used in blind schools; writes/identifies via embossed symbols.	Teaching aids Print media
Braille learning machine	Press-key input for braille typing; voice recognition function.	Teaching aids Typing and Reading
Fun Braille Learning Machine	"Whac-A-Mole"-style interactive device for playful braille learning.	Gameplay
Hybrid Braille Learning Machine	Combines braille input, touch panel, and braille display for IT accessibility.	Intelligent Simple design
Braille Notebook	Portable display with 16/24-cell input; supports notepad, file management, Bluetooth, etc.	Reading Typing
Smart Reader Audio Book Machine	One-button device for simultaneous braille and audio output.	Instant Reading Braille audio synchronization
Braille Computer	Liquid-crystal bubble display for touch reading; includes voice synthesis and touchscreen.	Comprehensive features

4.3.1. Create an "Instant Response" Touch and Hearing Linkage System

In the application scenarios of traditional Braille reading and writing devices, feedback delay is common. For example, when blind children touch the Braille dots to learn, they often have to wait for several seconds or even longer before the device gives corresponding feedback, which greatly interrupts the learning rhythm and leads to low learning efficiency. The real-time feedback mechanism system designed in this study can accurately match the touch actions of blind children. When the blind child's fingertips gently touch the Braille dots, the high-precision sensor built into the device quickly captures the action, and then starts the voice explanation function, which explains the meaning, pronunciation and other information of the corresponding Braille in a clear and standard pronunciation, truly achieving real-time feedback and intelligent guidance in parallel, laying a solid foundation for the efficient learning of blind children. Considering that the tactile senses of blind children are in the development stage, the sensitivity and accuracy are not yet mature. The research team designed wave grooves on the edge of the device. These grooves are regular and easy to perceive wave shapes. Blind children only need to gently slide their fingers along the edge of the device to perceive the direction of the grooves with their keen sense of touch, and then smoothly locate each function key, and easily carry out interactive operations such as switching learning modes and adjusting the volume. In the voice prompt link, we completely abandon the simple, cold and "wrong" prompts that lack effective information in the past, and strengthen the emotional voice broadcast function.

4.3.2. Building Intuitive Design and Multi-Sensory Guidance

From a human cognitive science perspective, human perception of the world relies on multi-dimensional sensory integration. For blind children with limited vision, touch, hearing, and synesthesia leverage neuroplasticity to enhance information processing. Neurological studies show that the tactile and auditory regions of blind children's brains expand and strengthen through long-term practice to compensate for visual loss. This design core aims to extend and cultivate blind children's sensory compensation abilities. However, current interactive designs for their devices lack depth, mostly offering basic functions without fully addressing their special needs.

This project innovates existing designs using intuitive design concepts and multi-sensory guidance strategies. Applying synesthesia theory, when blind children touch Braille to recognize semantics, the device provides accurate pronunciation feedback—e.g., touching "apple" triggers standard pronunciation and, if equipped, fruity aroma simulation. Through cross-sensory metaphor training, it helps build a "grapheme-sound-semantic" cognitive loop.

Considering the staged development of sensory compensation, the design incorporates progressive multi-sensory tasks. Divided into elementary, intermediate, and advanced levels based on reading/spelling proficiency, tasks range from tactile letter recognition with audio matching (elementary) to scene-based word interpretation (intermediate) and complex paragraph analysis using integrated multi-sensory inputs (advanced), addressing diverse training needs.

4.3.3. Promote Gamification Incentives and Cognitive Burden Reduction

The process of learning braille is often boring, which leads to a lack of motivation for blind children to learn. In order to effectively solve this problem, this design takes a unique approach and cleverly transforms the boring braille cognitive training into an interesting adventure mode. Based on the different learning chapters in the braille learning textbook, the game levels are carefully designed with different styles. For example, the basic braille letter learning chapter is set as the "Mysterious Letter Forest" level, and the blind children gradually unlock new paths by completing the task of identifying letter braille in the "forest"; the braille word learning chapter is made into the "Word Treasure Island" level, and the blind children need to spell the words correctly to dig for the "treasure". When the blind children successfully complete a certain number of correct tasks, the system will immediately give gamification incentives. This incentive form is rich and varied, which may be virtual gold coin rewards, which can be used to exchange learning props or decorations in the game store; or it may be unlocking new game character images to increase the fun of learning.

At the same time, this study recommends that the Braille reading and writing learning machine be included in the key promotion catalog of assistive devices in the National Disability Prevention Action Plan (2021-2025). Through close cooperation with the Disabled Persons' Federation and other relevant government departments, and through the procurement channels of the Disabled Persons' Federation, the equipment can be purchased in batches and supplied to the visually impaired groups and educational institutions in need, thereby effectively reducing the user's use cost and increasing the popularity of the product. At the same time, the industry-university-research cooperation mechanism should be strengthened, and universities and scientific research institutions should be encouraged to actively participate in the optimization and upgrading of products, continuously improve product performance and quality, and promote the healthy and sustainable development of the Braille education equipment industry.

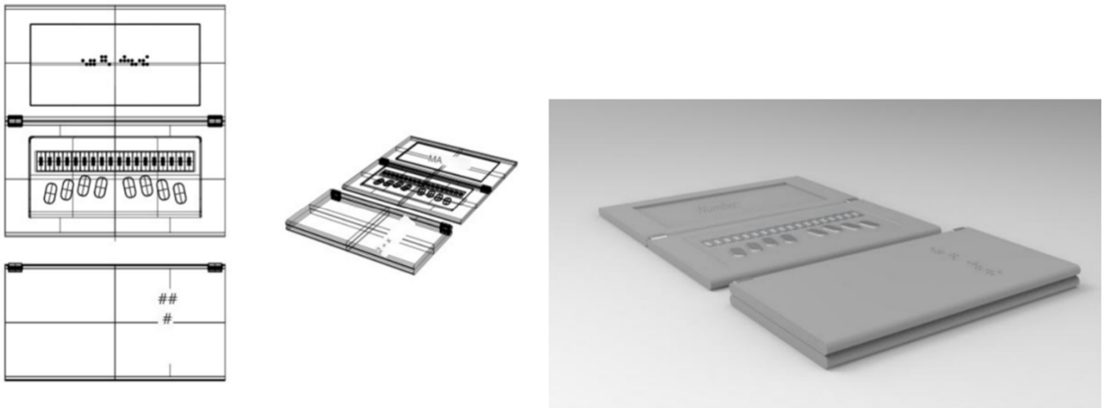

Fig 1. Rendering of the Braille reading and writing learning machine

5. Conclusion

Based on the barrier-free design methodology driven by the "user-technology-policy" trinity, this study successfully designed and developed a Braille reading and writing learning machine product. Through in-depth user research, accurately grasping the needs of the visually impaired group, integrating advanced technical means to achieve innovative design, and closely connecting with relevant policies, a solid foundation has been laid for the promotion and application of the product. Looking to the future, with the continuous innovation of AR/VR technology, exploring the deep integration of Braille learning machines and AR/VR technology has broad development prospects. For example, with the help of AR/VR technology to build a highly realistic virtual learning environment, provide visually impaired students with innovative functions such as virtual teacher gesture guidance and simulation of real learning scenes, further enrich the learning experience and significantly improve the learning effect. I believe that with the concerted efforts of all parties, Braille education equipment will continue to achieve innovative development and create a better learning and living environment for the visually impaired group.

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