Development and Application Study of a Tactile Interaction Service Framework for Blind Reading (Postprint)

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Abstract

[Purpose/Significance] In the process of promoting nationwide reading, meeting the reading needs of visually impaired individuals and safeguarding their reading rights carries important social significance. In response to the development trend in the internet era where people's reading habits and interests are expanding from traditional text to diversified forms including text, images, and graphics, this study proposes a haptic interaction service framework for blind reading by exploring issues related to blind reading and natural force-tactile interaction. [Method/Process] The haptic interaction service framework for blind reading, based on an analysis of haptic cognitive patterns and perceptual characteristics, focuses on elaborating key technologies in blind reading such as haptic object construction, intelligent haptic interaction, and haptic information presentation. By introducing a typical pen-based haptic rendering device, an experimental platform for haptic interaction services for blind reading is constructed, and experiments are conducted in stages on the effectiveness of haptic reading of information resources and the comprehensibility of information resources at different hierarchical levels. [Results/Conclusion] Experimental results demonstrate that the platform exhibits good immersion, interactivity, and feasibility in haptic reading of information resources for blind individuals; simultaneously, it verifies that information resources at different hierarchical levels present differences in difficulty regarding haptic reading and comprehension, and that the reasonable introduction of intervention training can effectively enhance operators' perceptual and recognition capabilities for information resources.

Full Text

Preamble

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Research on the Construction and Application of a Haptic Interaction Service Framework for Blind Reading
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Abstract

[**Purpose/Significance**] In the promotion of nationwide reading initiatives, meeting the reading needs of visually impaired individuals and safeguarding their reading rights hold significant social importance. As reading habits and interests in the digital age expand from traditional text to diversified forms including text, images, and graphics, this paper explores issues related to blind reading and natural haptic interaction, proposing a haptic interaction service framework tailored for blind reading. [**Method/Process**] The proposed framework analyzes haptic cognitive patterns and perceptual characteristics, focusing on key technologies in blind reading: haptic object construction, intelligent haptic interaction, and haptic information presentation. A typical pen-based haptic rendering device is introduced to build an experimental platform for haptic interaction services for blind reading, conducting phased experiments on the effectiveness of tactile reading of information resources and the comprehensibility of resources at different hierarchical levels. [**Result/Conclusion**] Experimental results demonstrate that the platform offers good immersion, interactivity, and feasibility for blind reading of information resources. The study verifies that information resources at different hierarchical levels exhibit varying difficulty in tactile reading and comprehension, while the rational introduction of intervention training can effectively enhance operators' perception and recognition capabilities for information resources.

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Keywords: digital information resources; blind reading; haptic interaction; haptic object construction; intervention training

Reading serves as a crucial means for humans to acquire, disseminate, and share knowledge, playing a vital role in enhancing national literacy and cultural heritage. In recent years, nationwide reading initiatives have gained increasing attention from the Party and government. The report of the 18th National Congress in November 2012 proposed "launching nationwide reading activities"; since 2014, the State Council has included "advocating nationwide reading" in its government work reports for four consecutive years; and the national "13th Five-Year Plan" has elevated nationwide reading to a national strategic level. From the perspective of reading subjects, nationwide reading encompasses all members of society. Therefore, in implementing specific measures and services for reading, it is essential to consider not only the reading needs of different age groups but also the varying reading abilities among different populations [1].

The Second National Sample Survey on Disability reports that China currently has 82.96 million people with disabilities, including 16.91 million with visual impairments, accounting for approximately one-fifth of the total disabled population. Consequently, addressing the reading needs of visually impaired individuals and protecting their reading rights in the promotion of nationwide reading initiatives carries significant social meaning and application value.

During reading, people primarily obtain external information through vision. For visually impaired individuals, due to visual impairment, they must rely on other sensory capabilities to compensate for the lost visual function. Current mainstream compensation methods fall into two categories: auditory and tactile. The former converts visual signals into audio signals for information transmission through text-to-speech, while the latter converts visual signals into tactile braille for perception, which represents the most fundamental reading method at present. However, in practical applications, this approach is limited by factors such as braille literacy rates, the quantity of braille reading materials, and reading speed. Compared to tactile methods, auditory approaches are more suitable for visually impaired individuals without hearing disabilities, requiring no specialized training and offering simple, flexible usage that is more easily understood and accepted. Moreover, this method holds certain advantages in terms of reading resources and speed.

Nevertheless, when facing the reading and comprehension of information resources such as images and graphics, existing compensation methods—whether auditory or tactile—have not adequately addressed these challenges. With the development of digital media technology and the widespread application of computer communication networks, images have become increasingly prominent as important information carriers in knowledge and information dissemination. Simultaneously, people's reading habits and interests have gradually shifted from traditional text forms to diversified content including text, images, and graphics. In response to this trend, how to leverage modern information technology to help visually impaired groups effectively recognize and learn information resources such as images and graphics has become particularly important.

This paper proposes a haptic interaction service framework for blind reading based on a literature review of blind reading and natural haptic interaction. By analyzing haptic cognitive patterns and perceptual characteristics, the framework elaborates on key issues in blind reading, including haptic object construction, intelligent haptic interaction, and haptic information presentation. Through experiments and application examples, it demonstrates the haptic rendering of information resources such as text, images, and graphics, and analyzes the experimental data. Finally, the paper briefly discusses existing problems and future research directions.

2 Literature Review

This section provides a brief review of research closely related to this paper from two aspects: blind reading and natural haptic interaction.

2.1 Blind Reading

With social development and technological advancement, the reading issues of special groups, particularly visually impaired individuals, have attracted increasing attention. Researchers have conducted relevant studies on blind reading from different perspectives. Lin Ying surveyed visually impaired individuals through questionnaires to understand their reading status and the social support they receive in reading [2]. In subsequent research, she further summarized three main reading methods for visually impaired individuals: tactile reading, visual reading, and auditory reading, analyzing the specific applicable populations for each method [3]. Li Xiao analyzed the current status of reading resource construction for blind individuals in China and elaborated on urgent problems in this area [4].

Since public libraries are important sources of information for visually impaired individuals, some scholars have focused their research on public library services for blind reading. Zhang Jingrong et al. examined disability user services in Canadian public libraries, paying particular attention to reading services for visually impaired individuals from perspectives such as special collections, assistive devices, and librarian services [5]. Wang Linjun analyzed promotional activities of Russian libraries for the blind, providing references for China's public library services for visually impaired readers [6]. Chen Yanwei analyzed the current status and existing problems of digital services for visually impaired readers in domestic public libraries, proposing improvement strategies from multiple perspectives [7]. Yuan Lihua used satisfaction of visually impaired readers as an important criterion for measuring the quality of barrier-free reading services, evaluating the effectiveness of barrier-free reading activities from the perspective of visually impaired readers [8].

Digital networks and information technology have provided new development opportunities for blind reading, with related research work gaining further advancement. Zhang Bingmei et al. investigated the reading time, methods, and needs of visually impaired readers through questionnaires, revealing a trend of transition from traditional braille paper reading to all-media reading, and discussed coping strategies for public libraries to improve barrier-free services for visually impaired readers [9].

Meanwhile, some researchers have conducted studies from the perspective of assistive reading devices, which mainly include electronic braille displays [10] and electronic tactile graphic displays [11]. The former dynamically converts ordinary text into braille to provide blind users with good text reading experiences; the latter presents images and graphics by replacing pixels in visual displays with tactile points. Considering that image presentation in electronic tactile graphic displays still follows traditional visual cognition methods, which fundamentally differ from how blind individuals understand images through finger touch, a research team at Tsinghua University [12] summarized and proposed design guidelines for blind tactile graphics from a user experience perspective to effectively enhance information acquisition efficiency during reading.

2.2 Haptic (Natural) Interaction

In recent years, with the continuous emergence of new interaction devices, the connection between humans and information spaces has evolved toward more natural, convenient, and efficient directions. Interaction interfaces have also experienced a development shift from humans adapting to machines to machines continuously adapting to humans, with human-centered natural user interfaces becoming the main direction for future human-computer interaction development. Similar to voice and visual interaction, haptic interaction, as a new form of natural interaction, has become increasingly significant in human information exchange and communication. With corresponding haptic devices [13-14], people can break free from the limitations of complex graphical user interfaces, bypass cumbersome menus and parameter selections, and touch, manipulate, and perceive objects in virtual scenes in a free and realistic manner, thereby obtaining good realism and immersion. Based on differences in human receptors, human haptic perception can be specifically divided into tactile sensation felt by the skin and force sensation felt by joints and ligaments [15], with these two sensations typically intertwining to exhibit interactive presentation. To simulate these two sensations, machines have developed tactile perception and force feedback technologies. The former primarily identifies touched objects through surface vibration, texture, and temperature, while the latter discriminates contacted objects through factors such as weight, hardness, and friction [16].

After decades of effort, haptic interaction has made considerable progress in both hardware and algorithmic layers. At the hardware level, various types of haptic interaction devices have emerged, from early force-feedback mice for desktop and Web experiences to current finger rings, haptic gloves, and other devices suitable for three-dimensional space and VR contexts [17-18], with miniaturization, naturalness, wearability, and flexibility gradually becoming the main trends in haptic interaction device development. At the algorithmic level, the introduction of the Phantom haptic device sparked research enthusiasm for haptic rendering methods, with typical algorithms including God-object [19] and Virtual proxy [20]. These algorithms have made virtual interaction between fingertips and various objects possible, providing unprecedentedly precise and convenient haptic stimuli. In recent years, haptic interaction has begun to integrate with specific application domains, showing a trend of diffusion from scientific professional fields to daily life. In serving visually impaired individuals, the most typical application is haptic navigation. J. Borenstein et al. [21] developed a navigation system called GuideCane for visually impaired individuals, which uses ultrasonic waves to detect surrounding obstacles and provides navigation information through vibration feedback inversely proportional to distance. O. Lahav et al. [22] introduced haptic feedback into blind orientation and mobility skills learning and virtual training, with studies showing that this method can help blind individuals construct effective cognitive maps and enhance their ability to recognize and explore unknown spaces. Regarding the accessibility of resources and services in museums, C.H. Park et al. [23] utilized haptic interaction combined with depth cameras and remote robots to build a remote museum access system based on haptic interfaces, enabling visually impaired users to remotely explore museum scenes and perceive 3D exhibits through haptic forms. In terms of abstract concepts, haptic rendering has been introduced into the learning process of scientific concepts and abstract geometric information to help people better understand basic knowledge, making learning more interesting and interactive. Major studies include: H.N. Kim and I. Han [24-25] presented physics-related scientific concepts such as heat, temperature, and force to visually impaired students through haptic methods. Compared with non-haptic simulation, multimodal presentation environments incorporating haptic feedback can effectively provide perceptual experience and achieve effective knowledge transfer.

The literature review indicates that previous research on blind reading services has primarily focused on theoretical discussions of current status, problems, and measures, with limited work at the application level. Meanwhile, theories and algorithms for haptic interaction technology have matured and gradually integrated with specific application domains. The author believes that the development and maturation of new natural human-computer interaction can provide new research perspectives and ideas for blind reading research, and intends to combine blind reading with natural haptic interaction technology to explore research work from an application perspective.

3 Haptic Interaction Service Framework

By introducing haptic (natural) interaction technology into the field of blind reading, the author proposes a haptic interaction service framework for visually impaired reading (see Figure 1 [Figure 1: see original paper]). The constructed framework is subdivided into five layers: data resource layer, operation processing layer, intelligent interaction layer, interaction device layer, and application service layer.

The data resource layer serves as the foundation for the upper four layers, providing necessary data support for upper-layer computations. It mainly consists of digital resources such as documents, images, and graphics, as well as real-time collected user behavioral data. Information about interaction devices is closely related to device selection in application scenarios. The operation processing layer is responsible for constructing digital resources from the information resource database into semantically clear and understandable haptic objects, while extracting features from interaction behavior data and generating operation sequences combined with interaction device information. The intelligent interaction layer is the core of the framework, primarily responsible for interaction between operation sequences and haptic objects, as well as perception and recognition of user intentions. The introduction of collision detection enables users to realistically touch and perceive object surfaces and corresponding features, achieving haptic interaction and information exchange. The interaction device layer mainly renders computed haptic information and transmits it to operators in the form of force or tactile sensations; visual and auditory auxiliary information presented in this layer can supervise the reading process of blind individuals, optimize and enhance cognitive reading effects, and assist visually impaired individuals with residual vision in haptic cognition. Taking the perception of a threaded wooden ball by a blind individual as an example, the basic flow of haptic interaction services is: first, digital resources are processed through a conversion mechanism into haptic objects, extracting contour features (spherical shape), material features (wooden), and texture features (spiral); second, the hand movement state of the visually impaired individual is transformed into user metaphors (such as 3D cursor, virtual hand) through motion mapping algorithms; then, collision status and region information between user metaphors and haptic objects in the virtual environment are captured in real-time, with tactile sensations and force conditions calculated based on touched contour, material, and texture features during reading; finally, analyzed haptic information is reasonably presented to fingertips or hand positions through haptic interaction devices. The application service layer is built upon the previous four layers to conduct services, including not only services that meet functional needs of visually impaired users but also novel service forms such as knowledge context simulation and cognitive ability training, satisfying users' reading needs at different levels. The five layers of the service framework progress layer by layer and complement each other, providing visually impaired users with natural, efficient, and intelligent haptic interaction service experiences.

In the following sections, the author elaborates on the core content of the middle three layers. Section 3.1 primarily describes haptic object construction in the operation processing layer; considering the extensive content in the intelligent interaction layer and the intrinsic relationship between information perception presentation and the interaction device layer, Section 3.2 on intelligent haptic interaction mainly involves collision position detection and intelligent intention understanding in Figure 1, while information perception presentation and related content of the interaction device layer constitute Section 3.3 on haptic information presentation. To ensure effectiveness in actual haptic reading, Section 3.4 introduces an intervention training mechanism to guarantee reasonable mapping between users' existing knowledge and haptic perception objects.

3.1 Haptic Object Construction

Considering human physiological characteristics and haptic perception features [26-27], how to construct semantically clear and understandable haptic objects from a haptic cognition perspective becomes particularly important. Haptic objects are mainly divided into three categories: text, images, and graphics. Their cognitive process should follow a principle of gradual progression from simple to complex. For text, the characters recognized by visually impaired individuals are primarily braille (also known as raised dots or embossed characters), a specially designed tactile script for blind individuals. Braille characters generally consist of six dots arranged in three rows and two columns, numbered 1, 2, 3 from top to bottom on the left and 4, 5, 6 on the right, with each braille character called a "cell." Research shows that braille used in current Mandarin Chinese includes current and double-pinyin systems, both belonging to the phonetic system [28]. Braille composition uses cells as units, with one Chinese character completed by several cells. The dilemma of braille publishing [29] and the low literacy status of blind groups reveal the importance of providing a digital tactile character recognition and reading solution. The author conducted surveys and interviews on the current status and problems of braille reading among visually impaired groups, obtaining the following insights: in the haptic construction of braille, special consideration should be given to tactile perception methods, dot spacing, cell spacing, and word segmentation, with relevant parameters adjustable according to readers' characteristics and cognitive habits. During specific learning and reading processes, learning and cognition of initials, medials, and finals in Chinese braille should be provided first, followed by progressive knowledge construction from characters to words, sentences, and passages. These insights can provide references for haptic construction of information resources such as images and graphics.

Images are the most critical component of haptic objects, as they help people construct an imaginative thinking mode for learning and problem-solving. Graphics are typically understood as two-dimensional presentations of simple raised shapes. Compared to images containing rich detailed information, the haptic construction of graphics is relatively simple, mainly involving shape contour features, so the author intends to discuss these together. Common image features include five categories: contour shape features, material features, texture features, color features, and spatial relationship features. The author classifies these features into hierarchical levels from simple to complex and from whole to part. During specific reading processes, visually impaired individuals can start perception from lower levels and independently select higher-level content according to their needs. The specific classification is: contour shape features and material features as the first layer, texture features and color features as the second layer, and spatial relationship features at the highest level. Contour shape primarily describes overall shape characteristics [30], while material manifests as surface roughness, hardness, and temperature information of contacted objects [31], both of which provide readers with an intuitive, global preliminary understanding. Image texture represents a local property of images or a measure of relationships between pixels in local regions [32]. In computer graphics, image texture mainly involves two aspects: uneven grooves on object surfaces and color patterns on smooth surfaces. The author focuses on the former, while color patterns and color features share commonalities and are discussed uniformly under color features. Since images are projections of real-world three-dimensional objects onto two-dimensional planes without height information, appropriate height information should be restored during haptic presentation of image textures to ensure reasonable protrusion and depression sensations.

Based on correspondence with relevant experts and reviewed literature, the author found that for visually impaired individuals (especially those with total blindness), color features are almost impossible to understand or perceive. Due to long-term visual deprivation, some individuals have relatively poor spatial thinking abilities. For the former, when necessary, research ideas from literature [33] can be borrowed to construct psychological effects of color and spatial perception. Studies show that psychological effects are influenced by subjective conditions and personality factors, but shared living conditions and social environments promote the formation of common psychological cognition. For instance, warm colors have an expansion effect, giving a sense of advancement, protrusion, and proximity, while cool colors produce the opposite effect, conveying retreat, indentation, and distance. From this perspective, different spatial distance sensations can be provided to readers during reading to achieve reverse mapping from spatial perception to color. Users can independently select these options according to personal needs to deepen understanding of details. To avoid excessive interference for users during initial image reading, the experimental phase of this paper focuses on the first three feature categories, temporarily excluding the latter two.

3.2 Intelligent Haptic Interaction

After constructing haptic objects, people expect to achieve information dialogue with haptic objects in various interaction contexts. During this process, how to accurately detect interaction positions, how to enable machines to intelligently understand human intentions, and how to provide natural and realistic interaction experiences are the problems we aim to explore and solve.

Based on differences in interaction contexts, interaction with haptic objects can be discussed from two dimensions: two-dimensional planes and three-dimensional space. A typical planar interaction context involves mobile terminals equipped with touchscreens, which have made significant progress in audio and visual interaction, providing extremely rich and diverse audio-visual information. However, in haptic interaction, any information presented on touchscreens has a simple, monotonous (glass) texture, with extremely limited or even absent tactile expression of information resources, making it difficult to satisfy visually impaired groups' desire to read and obtain information through touch in the new era. To address this pain point, researchers' overall approach is to use quantitative conversion models to transform visual information into haptic information and achieve haptic presentation at fingertips. Specific solutions can be divided into two categories: 1) starting from the touchscreen itself, adding haptic rendering panel layers to existing touchscreen structures to generate electrostatic haptic stimuli [34]; 2) designing wearable haptic rendering devices for mobile terminals [35]. Analysis of existing research results suggests that the latter is a potentially feasible solution in the current or near future. The basic flow involves direct interaction between users' fingertips and the touchscreen, obtaining target pixel points based on touch positions, calculating corresponding pixel feature information through image processing algorithms, and finally driving actuators of haptic interaction devices to produce controllable haptic interaction effects based on this information. In VR-represented three-dimensional contexts, haptic interaction is achieved through interaction devices (3D mouse, haptic gloves) using user metaphors (3D cursor, virtual hand, etc.) to operate virtual objects in realistic interactions. Unlike planar interaction contexts, in three-dimensional virtual space, two or even multiple objects may overlap spatially at the same moment, requiring collision detection algorithms [36] to determine whether contact occurs between user metaphors and haptic objects. To effectively improve algorithm efficiency, the detection process should be divided into two stages: coarse-grained detection and fine-grained detection. The coarse-grained detection stage should quickly eliminate haptic objects that definitely will not be touched to achieve preliminary filtering; for objects that may be touched during reading, fine-grained detection is needed to obtain the moment of contact and object surface positions. Finally, when contact or interaction occurs, the algorithm outputs necessary haptic information to ensure realism and immersion throughout the three-dimensional haptic reading process. Additionally, in planar interaction contexts, active interaction information such as finger posture and pressure should be emphasized based on tracking interaction points on the screen; in three-dimensional spatial contexts, diverse interaction operations between visually impaired individuals and haptic objects should be achieved from two levels [37]—selection (picking, scaling, etc.) and manipulation (grasping, translation, rotation, etc.)—based on touching and stroking information resources such as images and graphics.

Traditional interaction systems are machine-centered, with human cognition and operation loads being heavy during the overall interaction process, and interaction efficiency needs improvement. In haptic interaction services, we expect visually impaired individuals to gradually break free from machine-centered constraints, focusing their attention on information resources themselves during reading, and achieving "human-centered" interactive reading methods [38] through force or tactile information. Therefore, by drawing on the latest ideas from human-computer interaction, we attempt to introduce "intelligence" into haptic interaction to enhance machine (system) cognitive capabilities. The basic approach involves analyzing and extracting basic features of user operations, constructing algorithms to understand user intentions, and combining contextual knowledge to infer user interaction intentions in specific situations. Related research [39] also indicates that intention-driven systems can better improve interaction naturalness and efficiency while effectively reducing users' operational and cognitive burdens.

3.3 Haptic Information Presentation

Haptic information presentation is fundamental to haptic interaction services. Without force and tactile sensations, visually impaired individuals cannot effectively perceive information resources such as images and graphics. Specifically, it can be divided into two parts: haptic computation and haptic rendering. Haptic computation refers to analyzing tactile sensations and force conditions based on fingertip or user metaphor movements during reading, while haptic rendering uses haptic interaction devices to reasonably present haptic information.

Currently, simulation of temperature and vibration information in haptic perception technology is relatively mature. Taking vibrotactile feedback as an example, setting different frequencies and amplitudes can provide diverse tactile signals, which have been widely applied in cane navigation, smartphones, and VR controllers. However, when facing the touching and perception of information resources such as images and graphics, vibration feedback methods struggle to meet people's needs for high precision and immersive cognition during operation. Therefore, force feedback should be selected as the basic perception method for discriminating information resources such as images and graphics, with vibration feedback serving as an auxiliary reminder. When touching haptic object contours or manipulating haptic objects, users should feel tactile sensations, i.e., necessary reaction forces. Haptic object surface material depiction should consider both hardness and roughness. Hardness is adjusted through feedback force magnitude, while roughness can be simulated by adding friction opposite to the movement direction. Groove features of haptic objects are created by restoring surface height values of touched regions and modifying haptic signals based on gradient surfaces to generate tactile 凹凸感. For detailed information on haptic computation, please refer to previous research results [40].

Based on haptic computation, existing basic haptic rendering modes are divided into active and passive categories. Passive mode refers to automatic system responses under environmental factors or traction forces, generally independent of whether user metaphors contact objects. Active mode refers to operators actively exploring and perceiving when contacting haptic objects. The author believes that passive response and active perception should be combined as the basic framework for blind reading haptic processes. Regarding specific presentation devices, finger-worn, wearable, or pen-based haptic rendering devices can all serve as interfaces for reasonable presentation of force or tactile information, allowing users to independently choose according to their needs and conditions in practice.

3.4 Intervention Training Mechanism

For visually impaired individuals, acquisition of information such as text, images, and graphics is mostly completed through finger touch, which differs from how sighted people understand the world through vision. During actual haptic reading processes, researchers found that visually impaired individuals' haptic reading effectiveness is influenced by their existing knowledge structure, touch behavior preferences, and constructed haptic objects. Therefore, ensuring reasonable mapping between users' existing knowledge structure and perceived objects during reading is crucial and greatly affects reading effectiveness. Research shows that intervention training has a significant impact on people's knowledge acquisition and concept understanding [41]. Therefore, when visually impaired individuals encounter situations where perceived haptic objects cannot be effectively recognized under their existing knowledge structure, the rational introduction of intervention training provides an excellent solution. Figure 2 [Figure 2: see original paper] shows the flowchart of the intervention training mechanism proposed by the author.

During specific haptic reading processes, three scenarios may occur: 1) When haptic perception results deviate from or confuse with visually impaired individuals' existing knowledge structure, the intervention training mechanism needs to conduct intervention training to correct cognitive errors during reading and achieve reasonable matching of object cognition; 2) When visually impaired individuals perceive haptic objects but have no corresponding concepts in mind, they must learn and construct relevant concepts to achieve effective object cognition; 3) When existing knowledge structure is basically consistent with haptic object perception, no special intervention is needed for object cognition. Additionally, the intervention training mechanism should provide corresponding feedback functions that can further improve and enrich readers' knowledge structure in reading practice, enhancing cognitive efficiency for perceived haptic objects.

4 Experiments and Discussion

To verify the feasibility of the haptic interaction service framework for blind reading and analyze the performance of information resources in haptic reading and comprehension, this section designs and develops an experimental platform for haptic interaction services for blind reading (see Figure 3 [Figure 3: see original paper]), introducing a pen-based haptic rendering device for haptic information presentation while simultaneously presenting visual auxiliary information during experiments.

Thirty-four participants were recruited from Nanjing University with a 1:1 gender ratio and age range of 20-35 to eliminate gender and age effects on experimental results. Pre-experiment surveys showed that participants had neither haptic training backgrounds nor experience using haptic interaction devices. The experimental process consisted of two phases: the first phase invited volunteers to evaluate the experience effects of the haptic reading interaction platform; the second phase invited participants to complete experiments on the comprehensibility of information resources at different levels on the platform, with comprehensibility referring to (tactile) perceptual understanding of information resources—i.e., interpreting the meaning of currently perceived objects based on existing knowledge and experience and representing them with words.

4.1 Experimental Method

Participants wore eye masks to exclude visual influences on haptic perception. During experiments, operators used a pen-based haptic rendering device to control operation metaphors in virtual space (a 3D ball in this experiment) to "explore" various information resources. After experiments, for the first phase, the author collected operators' reading experiences through questionnaires; for the second phase, the author statistically analyzed operators' perception accuracy at each step, using a 10-point scoring system with 2 points for each successful match and 0 points for failures. Finally, interviews were conducted to exchange experimental feelings with participants and record them.

4.1.1 Effectiveness Experiment of Haptic Reading In the experiment, participants first wore eye masks to avoid visual influence on haptic reading. Then, without any training or verbal guidance, participants independently explored and perceived information resources in the virtual environment for 3-5 minutes. After the experiment, participants completed questionnaires consisting of two parts: collection of background information such as age and gender, and investigation of haptic reading effects, mainly involving factors including sensation of haptic objects, detail recognition, interestingness of haptic exploration, willingness for in-depth exploration, and friendliness of haptic interaction.

4.1.2 Comprehensibility Experiment of Information Resources Thirty-four participants were invited to the experiment. Before the experiment, participants received simple haptic interaction training and brief instructions about the experimental content. The entire experiment was divided into three different levels: contour shape perception, material perception, and texture perception. While blindfolded, participants first explored haptic objects at different levels based on their existing knowledge and experience. When participants could not effectively recognize haptic objects, the intervention training mechanism was introduced, followed by a second round of haptic object exploration. After the experiment, recognition accuracy rates for haptic objects in both rounds were statistically analyzed and compared.

Contour Shape Perception: Participants read five contour shapes in virtual space through haptic methods: semicircle, rectangle, triangle, trapezoid, and pentagon (see Figure 4 [Figure 4: see original paper]). The entire experiment lasted 5 minutes. After the experiment, participants matched corresponding contour shapes based on their perception experience, and matching success rates were analyzed.

Material Perception: Participants perceived five different materials in virtual space (mainly object hardness and friction information). The experiment lasted 5 minutes (see Table 1). After the experiment, participants selected corresponding material numbers based on their perception experience, and matching success rates were analyzed.

Texture Perception: Participants perceived texture information of tactile images (mainly surface groove information). The author selected five different texture images for the experiment (see Figure 5 [Figure 5: see original paper]), with the experiment lasting 5 minutes. After the experiment, participants selected corresponding image texture numbers based on their perception experience, and matching success rates were analyzed.

4.2 Analysis and Discussion

After the haptic reading effectiveness experiment, the author statistically analyzed questionnaires completed by participants to investigate and analyze reading effects of images and other information resources. Table 2 shows the evaluation of reading effectiveness of information resources under the haptic interaction platform. Survey results indicate that the experimental system enables users to feel haptic objects, satisfies users' needs for detail recognition, and helps them explore images and other information resources. Users highly recognized the system's ability to satisfy curiosity and its interesting presentation methods. However, in terms of human-computer interaction experience, less than 80% considered the experience good, representing the lowest overall recognition. Post-experiment interviews revealed that although the pen-based haptic interaction method can achieve haptic information presentation, its naturalness in human-computer interaction still has some distance from expectations. In practice, more natural haptic interaction devices such as finger rings or haptic gloves should be selected when conditions permit.

Table 3 presents sample statistics from the comprehensibility experiment of information resources under the haptic interaction platform. The mean data of correct perception before intervention training shows that the mean scores for contour shape, material, and texture decrease sequentially, indicating that information resources at different hierarchical levels exhibit differences in haptic reading and comprehension difficulty. Users have lower difficulty understanding contour shape features and higher difficulty understanding texture features. This also validates the reasonableness of hierarchical classification based on different feature comprehension difficulty during haptic object construction.

Table 4 shows paired T-tests for comprehensibility of information resources at different levels under the haptic interaction platform. When testing for significant differences between contour shape reading and texture reading effects, $t(34) = 8.212$, $p = 0.00$, indicating significant differences between contour shape features and texture features in user reading effects. When testing for significant differences between material reading and texture reading effects, $t(34) = 4.164$, $p = 0.00$, showing significant differences between material features and texture features in user reading effects. Finally, when testing for significant differences between contour shape reading and material reading effects, the results showed $t(34) = 1.089$, $p = 0.284 > 0.05$, indicating no significant difference between contour shape features and material features in user reading effects. These results also provide reasonable justification for classifying contour shape features and material features as the first layer and texture features as a higher layer in haptic object construction. After rational introduction of intervention training, the mean data of correct perception for contour shape, material, and texture all improved significantly (see Table 3). Results show that after intervention training, the perception accuracy rate for material features was the highest, while texture features showed the largest overall improvement.

Table 5 presents paired T-test analysis of comprehensibility before and after intervention training for information resources at different levels. When testing for significant differences in contour shape reading effects before and after intervention training, $|t(34)| = 4.176$, $p = 0.00$, indicating significant differences in user reading effects for contour shape features before and after intervention training. When testing for significant differences in material reading effects before and after intervention training, $|t(34)| = 5.250$, $p = 0.00$, showing significant differences in user reading effects for material features before and after intervention training. Finally, when testing for significant differences in texture reading effects before and after intervention training, $|t(34)| = 8.780$, $p = 0.00$, indicating significant differences in user reading effects for texture features before and after intervention training. When $df = 33$ and significance level $\alpha = 0.05$, the critical value is $t(34) = 2.032$, while the absolute values of all three T-tests in this study exceed the critical value, indicating significant differences in mean matching success rates before and after intervention training. This demonstrates that the proposed intervention training mechanism has a very significant effect on improving recognition accuracy rates for haptic objects.

Through analysis and discussion, it can be found that the haptic interaction experimental platform built based on the haptic interaction service framework can basically meet users' needs for perceiving, exploring, and reading haptic objects. Differences in haptic reading and comprehension difficulty among information resources at different levels such as contour, material, and texture also validate the reasonableness of the feature classification and hierarchical approach adopted in haptic object construction. In the reading process of information resources, when haptic objects cannot be effectively recognized, the rational introduction of cognitive training mechanisms can effectively enhance operators' perception and recognition abilities for information resources, providing a good guarantee for the effectiveness of haptic interaction reading services for visually impaired users.

5 Conclusion and Outlook

The author proposes a haptic interaction service framework for blind reading, analyzing haptic cognitive patterns and perceptual characteristics, focusing on key issues in blind reading such as haptic object construction, intelligent haptic interaction, and haptic information presentation, and demonstrating haptic rendering of text, images, and graphics through experiments. Experiments show that the implemented haptic interaction platform exhibits good immersion, interactivity, and feasibility for blind reading of information resources, while verifying that haptic information resources at different hierarchical levels exhibit differences in reading and comprehension difficulty. During the reading process of information resources, when haptic objects cannot be effectively recognized, the rational introduction of cognitive training mechanisms can effectively enhance operators' perception and recognition abilities.

The limitation of this study is that experiments on the effectiveness and comprehensibility of information resource reading were conducted by having participants wear eye masks to simulate visually impaired reading and exclude visual influences on haptic perception. The scientific validity of experimental results would be further enhanced if actual visually impaired participants were selected, making the results more convincing. Factors such as age may also have certain impacts on experimental conclusions, as cognitive abilities and haptic/force control may differ across age groups.

This study integrates the novel haptic interaction modality into blind reading, leveraging the enhancement and complementary effects between sensory channels to help visually impaired users overcome perceptual barriers to information resources and improve the accessibility of data resources and services, promoting equitable supply of public cultural services. In practice, it explores multimodal presentation and natural interaction of data resources in three-dimensional contexts (audio-visual-touch), constructing a relatively complete framework methodology system. The research results can provide references for research and practical activities in social and cultural fields such as libraries, museums, and archives.

Future research will primarily focus on hierarchical perception algorithms for tactile images, construction of multi-level interaction operations, and experimental comparisons of haptic reading among visually impaired groups of different levels (blind, low vision, etc.), different causes of blindness (congenital, acquired), and different age groups (children, youth, middle-aged, elderly) to explore the laws of blind haptic reading and information resource cognition.

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Qi Binbin: Proposed research ideas, designed paper framework, designed experiments, wrote and revised paper;
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Abstract: [Purpose/significance] In the promotion process of civil reading, it is of great social significance to meet the reading needs of visually impaired people and ensure their reading rights. With the advent of the Internet era, people's reading habits and interests begin to expand from traditional texts to diversified forms such as words, images, and graphics. [Method/process] This paper discusses related problems of blind reading and presents a novel tactile interaction framework for blind reading. The tactile cognition and perceived characteristics are firstly analyzed and then a set of key issues about blind reading are elucidated. By introducing a typical force feedback device to build a tactile interaction system, the experiment is comprised of two stages: the effectiveness of tactile reading and the comprehensibility of information resources at different levels. [Result/conclusion] Experimental results showed that the tactile interaction system has excellent performances in immersion, interactivity, and feasibility. It is proved that there are differences in the difficulty of tactile reading and comprehensibility of information resources at different levels, and the rational introduction of cognitive training mechanism can effectively improve the operator's perception and cognition ability.

Keywords: digital information resources; blind reading; haptic interaction; haptic object construction; intervention training

Note: Figure translations are in progress. See original paper for figures.