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Research on Multimodal Interaction Design Patterns for Visually Impaired People Under Sensory Compensation Theory

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Abstract. Based on the theory of sensory compensation, this paper mainly applies the multimodal interaction design method to solve the difficulties and challenges faced by the visually impaired people watching the game as an application scenario, so as to provide a reference for the accessibility design. In terms of research ideas, the technical principles and applications of visual enhancement, auditory compensation, tactile compensation and olfactory compensation are investigated by combing the development of sensory compensation and the three realization methods of visual enhancement, visual substitution and visual replacement for visually impaired people. By dividing the game-viewing scene into five sub-scenes to gain insight into the specific needs of visually impaired people, combining the needs with the three forms of application of sensory compensation mentioned above, discussing their adaptive relationship with different scenes, and exploring the multimodal interaction design mode under the different needs of visually impaired people, in summary, this research come up with the design of the multimodal interaction system for the visually impaired people used to watch the game. The design example verifies that the multimodal interaction design mode based on sensory compensation design with intersecting and complementary senses of vision, audio, and tactility can help to improve the quality of spectator services and daily travel and life of the visually impaired people.

Keywords. Sensory compensation, visually impaired people, multimodal interaction design

In recent years, technology has been gradually integrated into the construction of spectator scenes and the design of facilities for the visually impaired, including tactile flooring, sound guidance systems, etc., which provide richer services for the visually impaired at the tournaments, however, there is still room for expanding and deepening the interaction mode. This paper will focus on the obstacles faced by the visually impaired in daily lives, and promote the research and application of product and service design that meets the needs of the visually impaired through the study of the theory of sensory substitution and sensory compensation to create a multimodal interaction system. The research aims to solve the problems of access to information, travel, object recognition and spatial perception for the visually impaired; To construct a journey scenario for the visually impaired to watch the game, design intelligent products and interface systems that optimize the output of information, ensure worry-free travel, and provide a multi-sensory game-viewing experience and multi-modal interaction.

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1. Sensory compensation theory: mechanism underpinning sensory substitution

Since the 19th century, scholars suggested that the visual deficit could be compensated for by one of the remaining senses [1]. William Hanks Levy, a British educator and blind writer, first proposed the "five senses" as a systematic element of sensory compensation for the blind. According to this, the relationship between the human brain and the five senses of sight, hearing, touch, smell and taste is like the relationship between a battery and five wires; in the case of blindness, the total energy of the "battery" is distributed to only four "wires", resulting in the rest of the senses having a stronger ability to acquire information [2]. At that time, a number of scholars argued that sensory compensation for the blind was primarily based on hearing and touch, but most of these were based on empirical descriptions rather than on experimental studies.

Until the 1970s, Prof. Paul Bach-y-Rita, University of Wisconsin System, through experiments to prove the substitution relationship among the "five senses", not only proved the possibility of sensory compensation, but also clearly put forward the theory of sensory substitution. In the experiment, 400 matrix-arranged tactile stimulators mounted on the back of the chair were able to project images scanned by a camera onto the back of blind person, enabling the blind to accurately perceive and describe the layout, depth and placement of objects in space. This led him to propose the concept of "sensory substitution", one sensory modality (mainly tactile) is utilized to obtain environmental information for use by another sensory modality (mainly visual), which was published in Nature [3]. Subsequently Paul Bach-y-Rita and others developed the first sensory substitution system, arguing that visually impaired people can feel image information through their skin [4]. Following this pioneering experiment, researchers discovered that different skin regions of the body including abdomen, back, thighs, forehead or tongue can be used as sensory organs for visual input [5]. These studies have provided important references for the design of visual substitution devices, and scholars have successively investigated a number of auditory substitution programs for vision, such as the vOICe (the capitalized letters spelling “Oh, I see!”) technology auditory device [6] and the prosthesis substituting vision with audition (PSVA) [7], both of which are based on the principle of utilizing a head-mounted video camera to capture visual frames in real time as it moves, and convert them into a set of corresponding sounds, so the testers can achieve visual recognition. Tactile and auditory sensory substitutes in effect convey only grayscale visual information, and while luminance is sufficient to accomplish the perceptions of shape recognition, object localization, and distance estimation, saturated color can enliven the picture. An early device that mapped the image to a specified color and then played a recording of that color could be considered a non-sensory assistive technology. For sensory substitution of smell, a unique type of perceptual processing, experiments have demonstrated that image perception can be generated through odors, especially after associative learning between perceived odors and their names [8].

There are still many unresolved issues in this research field, and the exploration of body parts in the theory of sensory substitution is continuing and expanding. In fact, in the process of perceiving and using products, people's senses such as vision, hearing, touch, taste and other senses do not simply play their own roles, but rather, they are integrated and shaped by each other, and when one of the human sensory organs is damaged and unable to play a normal role, as a kind of physiological compensation, certain other senses may have functions beyond the normal human being, so that as far as possible, the human being will be able to get the corresponding ability, and this is the phenomenon of sensory substitution.

2. Sensory compensatory design pathways and technical principles

Sensory compensation theory was applied to the design field at the beginning of the 21st century, especially with the development of barrier-free design and aging design, and has been widely adopted as a universal feature, mainly in human-computer interaction (HCI) research. Currently, there are three ways to help improve the lifestyles of the visually impaired, which can be categorized according to the utility: visual enhancement, visual substitution, and visual replacement. These are discussed in the following sections.

2.1. Visual Enhancement

A large proportion of visually impaired people are not completely blind and have some ability to see, they just don't see things clearly. Although the industry has long used color filters or contact lenses to help visually impaired people add brightness to restore some vision in certain situations, they are not adapted to all shades of color. In recent years, researchers have found that accurate spectral separation and acquisition of different frequency band image information can be achieved using multispectral imaging, and the imaging results can reflect the vision of normal people and color-blind people [9], which can help visually impaired to increase the brightness and color in order to restore part of their vision. Incorporating multispectral lenses into the product design allows visually impaired people to access spectral information for better object recognition.

2.2. Visual Substitution

Visual substitution is similar to visual enhancement, but the output is non-visual, as tactile, auditory or others. Since senses such as tactile have a much lower information capacity than vision, the information must be processed to a level that the user can handle.

- Auditory Compensation

Hearing is second only to vision in obtaining external information, has the most direct and rapid characteristics. The vibration of air molecules creates sound waves, and the auricles can pick up vibrations coming from any direction and transmit to the brain via the auditory nerve. It has been shown that auditory compensation for the blind is a spatial attention mechanism that is enhanced when the visual system is completely deprived, which contributes to the improvement of different auditory abilities such as sound discrimination, speech recognition or auditory spatial localization [10]. The use of auditory surrogates in design can give visually impaired assistance in avoiding obstacles in traveling, reading text, and exhibiting guides, e.g., by using cars with artificial voices to help visually impaired warn of the vehicles that are coming and going. Researchers have utilized the Google Vision API to convert images captured by a built-in camera into digital text and the TTS (Text to Speech) library to convert text into audio [11] to overcome dyslexia in visually impaired. In recent years, some museums have also implemented interactive technologies to automatically play audio guides and descriptions through infrared sensing technology to meet the visually impaired' needs when visiting museums.

- Tactile Compensation

Tactile compensation is a more prevalent form of compensation in current research. Physiologically, the sense of touch is a pattern of integrated information from receptors and nerve endings concerned with pressure, temperature, pain and movement. Tactile perception is primarily associated with the pressure sensation (from mechanoreceptors), not only the smoothness, roughness, size and shape of an object's surface, but also the spatial awareness sensed from the internal sensation of body position, movement and balance, so that tactile is a communicative sensation that is receptive, expressive, communicative, and empathic. Tactile compensation refers to the use of senses such as forehead, hands, feet, back and even tongue to help visually impaired people recognize the shape of objects and spatial perception in the form of touch or stimulation signals, which can be realized through material and texture. In mobility design, the combination of white cane and blind can assist visually impaired people to avoid obstacles, and German designer Jakob Kilian developed a sensory surrogate glove device that transmits the relative positions and distances of nearby objects as vibratory stimuli to the back of the hand, assisting blind people in navigational tasks such as object recognition and wayfinding [12]. The sense of tactility is more realistic and subtle than vision, and and a more genuine perception can be obtained through contact.

- Olfactory and Gustatory Compensations

In human coordinates, smell is a sensory sensation that can be realized at a distance, while taste is a close sensation. Since the senses of olfaction and gustation are mainly formed by the accumulation of life experience, the design for olfaction and gustation is characterized by uncertainty and individual differences, which is more difficult to be realized in the sensory compensatory interaction design for the visually impaired group.

In addition to the visual enhancement and visual substitution, the use of non-sensory forms of visual replacement is one way to enhance the blind' vision. As it relates to scientific, technical and medical issues, this category will not be discussed in this article.

It can be seen that there is still a lot of space for the research on the development of sensory compensatory design theory, and the application in design is still improving. From a comprehensive point of view, the single-sensory alternative mode and its products can no longer satisfy the diversified living environments and needs of the visually impaired, so this paper is mainly based on the theory of sensory compensatory design, and researches on the multi-modal interaction design mode of multi-sensory interaction in different scenarios, to solve the obstacles of the visually impaired people's viewing problems, and to provide theoretical references to the accessibility design of the visually impaired people and the design of sensory compensatory design.

3. Multimodal interaction design for visually impaired people

3.1. Needs based on visually impaired people

Visually impaired people are those who have visual impairments, including visual field disorders, color vision disorders, etc. In fact, a large proportion of visually impaired people still have some visual function, but the things they see are not very clear. With reference to psychologist Maslow's hierarchy of needs, and taking into account the psychological and social characteristics of the visually impaired, they are categorized into three levels of needs. The first need of the visually impaired is the "safety need", which means that the user is safe and secure. The second demand is "interaction demand", which means that the visually impaired should maintain good interaction language and behavior, such as easy-to-understand language, simple operation process, and so on. The third need is the "spiritual need", which means that the visually impaired is treated with care and respect. Successful interaction design can help visually impaired use products more easily and improve their quality of life, so interaction needs are crucial in their life.

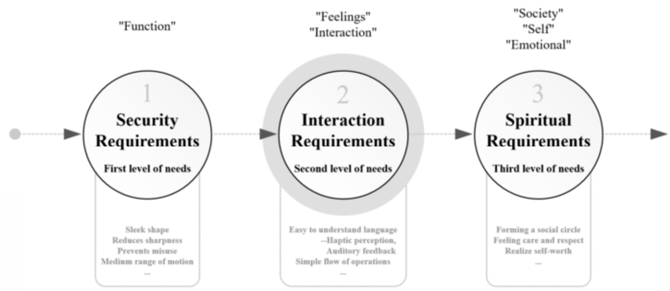

Figure 1. Hierarchy of needs of the visually impaired.

3.2. Multimodal interaction

The term "modality" means "senses", and multimodality means the fusion of two or more senses, which means human-computer interaction through multiple modes such as vision, hearing, smell, touch, environment, and so on, and is one of the channels through which human beings can obtain information through their experience and senses. It was first proposed by German physiologist Hermann von Helmholtz (1821-1894). Multi-sensory perception is able to provide complementary information from one sense to that from another compared to uni-sensory perception, and the combination of the obtained multi-sensory perceptual information enables more accurate estimation of information about an object in space, such as the enhancement of the perceptual experience of a touch screen button by combining visual and complementary audio/haptic feedback.

Any sensory information that peoples receive while interacting with a product that has been intentionally or unintentionally created can have an impact on the perception, cognition, experience and behavior of the product [13]. Since each sense can provide complementary information that is difficult to be captured by the other senses, multisensory experiences allow people to synthesize multisensory information more closely and deeply in order to understand their surrounding environments and situations, and in addition, multisensory compensation methods that combine multiple senses such as tactile, auditory, and vestibular senses in place of vision can bring positive emotions to the user, and the infinite possibilities of multisensory joint compensation pathways should be actively explored and applied to a wide variety of scenarios.

3.3. Multimodal Interaction Design System under Sensory Compensation

- Interaction scenarios for the visually impaired

User, behavior, tool or medium, purpose, and scenario are the five basic elements of interaction design [14]. Scene is an extremely important element in the interaction system, and it is an important goal of interaction design to study user behavior in a specific scene, and to plan and design user behavior logic for the corresponding scene. The large scene is relatively macroscopic, which can overview the user's macroscopic needs; while the small scene is more focused and concrete, which can provide insights into the more specific needs of the user, as well as reflecting the user's specific behavioral processes and detailed experience of the product, which facilitates the designer's targeted design under the target scenario [15].Based on the above, this paper subdivided the game viewing scenario into five small scenarios, namely, at home, on the way, outside the stadium, during the game, and after the game, and investigated the five basic elements of the interaction of visually impaired people in the five small scenarios, namely, the user, the behavior, the tool or medium, the purpose, and the scenario, to summarize the pain points, opportunity points, and needs of the visually impaired people who are currently facing the game viewing, as shown in Fig. 2.

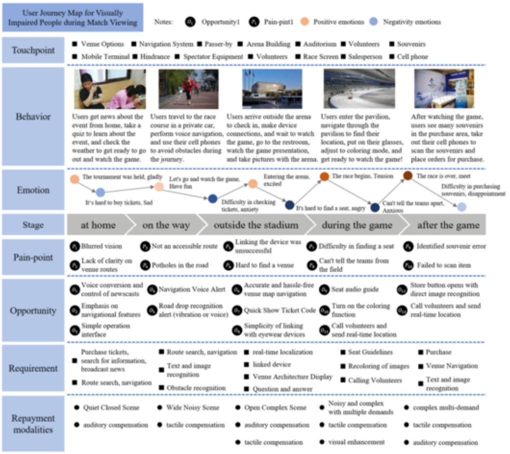

Figure 2. Design Challenges for Visually Impaired People in Game Viewing Scenarios.

- Multimodal Interaction System Design

Seeking the goal of hassle-free viewing for the visually impaired based on accessibility, research and practical experience have shown that the implementation of multimodal interaction design has facilitated changes in service delivery. Together with the use of assistive technology, inclusive practices, and multisensory surrogates, it can improve the behavior and socialization of visually impaired people during game viewing, in addition to reducing wasted time. Combined with the above research on user pain points, opportunity points and needs, the user needs are categorized into four modules: tournament, navigation, barrier-free viewing and calling, and set as the main entrance of the user interaction interface, categorize the 15 user needs mentioned above according to these four modules as the first-level content, match the relevant technology according to user needs as the second-level content, and ultimately decide to form a visually-impaired people's tournament-viewing system by the interaction app end and the device end.

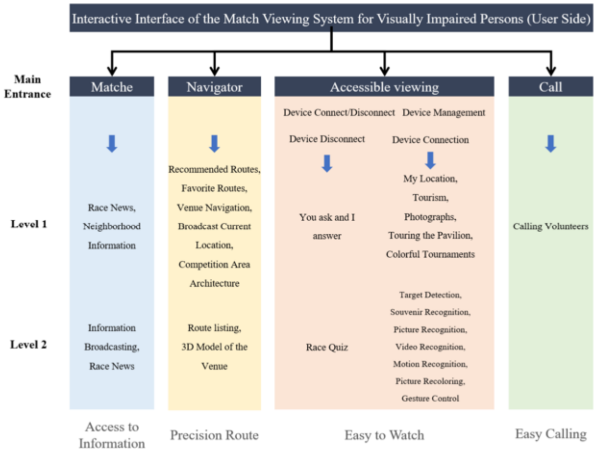

Figure 3. User Interface Information Architecture.

Four modules are constructed according to the requirements module in the information architecture diagram, as input user requirements, task operation, output results and completion of user requirements, in order to complete the flowchart of the interactive interface of the viewing system for visually impaired people.

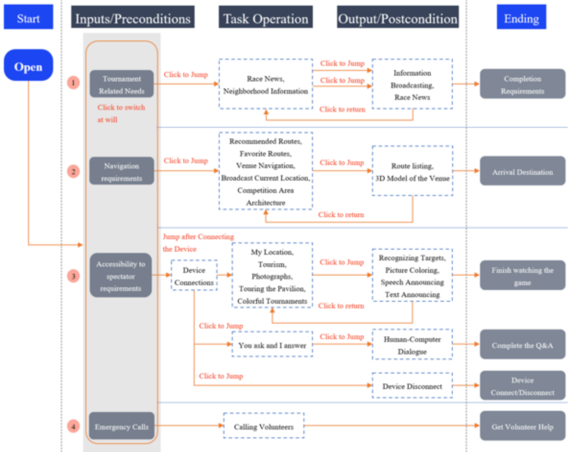

Figure 4. Flowchart of the user interface.

Figure 5. Interactive system interface diagrams.

4. Usability Testing of Interactive Interfaces for Visually Impaired Game Viewing Systems

Usability testing is an important part of the design practice to test the usability of the interactive interface of a multimodal visually impaired crowd viewing system under the theory of sensory surrogacy.

4.1. Selection of test subjects

A total of 6 visually impaired were invited to test the interactive interface of the game viewing system for the visually impaired, including 2 blind and 4 visually impaired people aged between 20-40 years old. The above six visually impaired have the ability to operate smart phones and are interested in sports events. By inviting target users to use the prototype, observing their performance and recording their ratings on the four test specifications, namely, user friendliness, validity, fault tolerance, and satisfaction, we can obtain effective feedback and continuously improve the interaction design of the viewing system for the visually impaired.

Table 1. Test metrics.

Test dimensions	Test metrics
User friendliness	Is the product easy to operate and learn
	Is the information layout of the interface clear
	Are there steps in the interface that are not understood
Validity	Whether it is effective in helping users accomplish their tasks
	Is there a good function guide in the interface
	The simplicity of the flow of operations in the interface
	Whether there is timely feedback after the operation is completed
Fault tolerance	Is there frequent misuse during use
	Clarity of solutions when misuse occurs
Satisfaction	User satisfaction with the product
	Willingness to continue using this product

4.2. Designing test tasks

According to the functions of the interactive interface of the game viewing system for visually impaired people, the following seven tasks were developed, including get race information, venue route navigation, viewing device connection, enhanced color vision for the visually impaired, take a picture to recognize objects, venue tours and guided tours, and calling volunteers. The testers were required to perform at least four tasks, and upon completion, they were asked to give their feedback and feelings according to the Comprehensive Experience Completion Task Evaluation Form.

Table 2. Test tasks

Mission details	Mission path
1.Get race information	Home--Events--Information Reading
2.Venue route navigation	Home - Navigation
3. Viewing device connection	Home--Accessible Viewing--Connected Devices
4. Enhanced color vision for the visually impaired	Home--Accessible Viewing--Colorful Viewing
5. Take a picture to recognize objects	Home--Accessible Viewing--Picture Taking
6. Venue tours and guided tours	Home--Accessible Viewing--Accessible Venues
7. Calling volunteers	Home--Emergency Call

4.3. Test Methods and Analysis of Results

The interface prototype for this test was created by Axure RP. After production, a QR code containing the address is generated by uploading it to the Axure cloud, and the QR code was scanned with a smartphone for simulation testing of the interface prototype. The Likert scale method was first introduced by psychologist Rensis A. Likert in 1967 and has been widely used in quantitative research in the social sciences. The method is based on constructing a series of declarative sentences describing the situation of a certain viewpoint or behavior and asking the tested users to choose one answer among five levels, where 5 is the highest score representing very satisfied, 4 is quite satisfied, 3 is average, 2 is dissatisfied, and 1 is very dissatisfied, to obtain the user's attitudes and evaluations of the viewpoint or behavior and to collect the results of the ratings, so as to summarize the strengths of the system's design and the areas that need to be improved.

After the completion of the above tests, all the test results were organized, which shows from the data that the users evaluated the various dimensions of the system interface well. The highest rating among the four dimensions is the user satisfaction with the product, and most users indicated that they have a good overall feeling about the product and are willing to continue to use it; the effectiveness score is 4.6, and users indicated that they can complete the expected tasks and have a good feedback mechanism; due to the existence of multiple operation steps in the same interface, which leads to misoperation of the visually impaired people, it is possible to set up uneven cell phone planes to help the visually impaired people differentiate the function positions, or adopt the pop-up confirmation frame and auditory guidance interaction to improve the fault tolerance of the visually impaired people's operation process. In terms of overall ratings, the design solution for this topic largely met expectations.

Figure 6. Usability Testing Process.

Table 3. Test results.

Test dimensions	Test metrics	Average score for each	Average score
User friendliness	Is the product easy to operate and learn	4.8	4.4
	Is the information layout of the interface clear	4.5	
	Are there steps in the interface that are not understood	4.0	
Validity	Whether it is effective in helping users accomplish their tasks	4.6	4.6
	Is there a good function guide in the interface	4.7	
	The simplicity of the flow of operations in the interface	4.3	
	Whether there is timely feedback after the operation is completed	4.8	
Fault tolerance	Is there frequent misuse during use	4.0	4.1
	Clarity of solutions when misuse occurs	4.2	
Satisfaction	User satisfaction with the product	4.6	4.7
	Willingness to continue using this product	4.7	

5. Conclusion

With the continuous development of technology, scholars have found that tactile or auditory compensatory modes can realize the visually impaired people's perception and communication of visual images, and the abdomen, back, thighs, forehead or tongue can be used as the sensory organs for visual input. Combined with the technologies of target detection and motion recognition, it can provide visually impaired with diversified information perception modes, and the multimodal interaction mode, which integrates visual enhancement and visual substitution and other sensory compensatory methods, can better satisfy the obstacles and needs of the visually impaired in the game-viewing scenarios than the single-sensory interaction mode. When designing the viewing system for the visually impaired, in addition to meeting the functionality, more attention should be paid to the interaction needs of the visually impaired to optimize the user's sensory experience and service level.

This study provides guidance for solving the problem of game-viewing for visually impaired and constructing multimodal interaction modes, and also proposes multimodal interaction design modes for different scenarios. Visual enhancement and auditory compensation interaction modes are used in the game viewing scenarios; visual enhancement and tactile compensation interaction modes can be used for navigation in open scenarios; and auditory and tactile multimodal interaction modes can be used in relatively quiet and closed scenarios. It also provides a reference for the accessibility design in future scenarios. With the continuous optimization and updating of interaction modes in product design, exploring the multimodal interaction modes of products for the visually impaired and their user experience research will become one of the hot spots of design research, and the multimodal interaction design modes of products for the visually impaired will be more diversified and perfect in the future.

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