Research on Design Strategies of Wearable Devices for the Visually Impaired

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Abstract. Acknowledging the significant role of wearable devices in aiding the visually impaired, this study provides a comprehensive overview of design methods and theoretical frameworks specific to this demographic, aiming to guide future research and practical applications. The paper posits that integrating multichannel sensory design strategies in the initial design stages can facilitate innovative human-computer interactions with low cognitive load and high efficiency. Furthermore, incorporating participatory design, inclusive design, and emotional design theories into the development of wearable devices for the visually impaired can enhance their human-centric nature, thereby improving acceptance and engagement among visually impaired users.

Keywords: wearable, visually impaired, multi-sensory integration, accessibility, human-centered.

1 INTRODUCTION

Visual perception is a primary means by which humans gather environmental information, significantly influencing quality of life, social interactions, cognitive development, and emotional experiences. Individuals with visual impairments lack this capability, necessitating societal attention. According to the 2019 Global Burden of Disease study, by 2020, there were approximately 43.3 million blind individuals globally and 295 million people with moderate to severe visual impairments. With population growth and aging, these numbers are projected to rise to 61 million and 474 million by 2050, respectively [1]. Visual impairments not only affect individual quality of life but also pose societal challenges. Beyond medical, neuroscience, and biotechnology achievements in addressing visual impairment, design interventions can enhance the quality of life for visually impaired individuals and promote social integration. Recent developments in wearable technology have integrated these technologies into Affective Computing, primarily for activity recognition, perception, and emotion detection. This integration provides a deeper understanding of human behavior and emotions and reveals the broader application potential of wearable technology, particularly in rehabilitation and assistive devices. Despite substantial research on wearable devices for the visually impaired aimed at improving mobility safety and visual recognition, key issues

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remain overlooked. Specifically, existing research often lacks a comprehensive theoretical framework and neglects the perceptual, emotional needs, and personal preferences of users. This mismatch can affect user attitudes and satisfaction. Therefore, addressing these issues and enhancing social support for the visually impaired is urgent and important.

2 OVERVIEW OF WEARABLE DEVICES FOR THE VISUALLY IMPAIRED

Intelligent wearables are miniature electronic computers that can be worn or attached to the user, utilizing built-in sensors to monitor environmental parameters and biological indicators in real-time, thus forming a body-data interface. Technological advancements have expanded the application scope of wearable devices, from basic health monitoring to medical applications and task-oriented tools like guide devices. The core function of wearable devices for the visually impaired is the active perception of surrounding environmental information. Currently, visually impaired individuals primarily use two aids for mobility and daily activities: white canes and guide dogs. Although handheld white canes detect obstacles through tactile feedback, their detection range is limited and insufficient to address most challenges faced by visually impaired individuals in daily life. Guide dogs help owners avoid obstacles and navigate, also serving as a bridge for social connections and providing emotional support. However, the high training costs and caretaking responsibilities make guide dogs less accessible to most visually impaired individuals. In the era of the Internet of Things and Artificial Intelligence, combining wireless network technology and environmental sensing can help visually impaired people overcome visual deficiencies. Additionally, wearable devices offer diverse wearing methods and can flexibly adapt to different body types, carrying capacities, and wearing occasions. The popularization of wearable devices for the visually impaired is expected to broaden their range of daily activities, improving their mobility, social interactions, and overall life experiences.

3 SENSORY DESIGN STRATEGIES FOR WEARABLE DEVICES FOR THE VISUALLY IMPAIRED

Human senses are the windows through which we perceive the world. For visually impaired individuals, sensory design strategies aim to compensate for visual deficiencies through other sensory channels. These strategies primarily involve sensory substitution and sensory enhancement.

3.1 Overcoming Visual Impairments with Sensory Substitution

Researchers have long sought methods to substitute vision for the blind. In the 19th century, Paul Bach-y-Rita developed a system that allowed blind individuals to perceive visual information through touch, proposing the Theory of Sensory Substitution.

This theory explains how information can be transferred across different sensory modalities. Sensory substitution has become an effective way to address technical challenges from a design perspective.

In sensory substitution design for the visually impaired, auditory channels offer the advantages of being both natural and instinctive. They are non-intrusive, support multitasking, and facilitate emotional communication. Depending on users' auditory memory capabilities, the sound systems can enhance attention and memory by replaying information. Besides standard verbal broadcasts of information such as text or navigation routes, auditory stimuli like pitch and tone variations can provide alternative visual inputs for the visually impaired, expanding their semantic understanding.

Compared to auditory, the tactile channel is less constrained by cognitive limitations in information processing. Tactile Vision Substitution Systems (TVSS) are widely applied. For visually impaired individuals, auditory information requires sustained attention and is vulnerable to noise, whereas tactile information processing can separate information from environmental noise, reducing cognitive load. Tactile feedback can alert users or indicate directions, such as vibration frequency for distance [2], skin stretching for angles [3], and continuous sensations for direction [4]. TVSS is also efficient in conveying simple information. By mapping visual information to skin sensations, wearable devices can naturally convey environmental, navigational, and social information, aiding the visually impaired in better perceiving the world around them.

3.2 Enhancing Sensory Experience with Sensory Enhancement

Perception enhancement is a method that strengthens the functions of normal sensory systems through technology or devices. This enhancement not only increases the sensitivity of existing senses but also adds new perceptual capabilities. For example, Hu et al. [5] designed a wearable device that simulates natural sound waves based on humans' ability to perceive sound source locations, effectively enhancing the spatial perception abilities of the visually impaired. For individuals with low visual sensory capabilities, such as those with color blindness or low vision, sensory enhancement methods can amplify and increase contrast to help them acquire information.

3.3 Reducing Cognitive Load with Multichannel Sensory Design

Most wearable devices rely on sensors for interaction. These sensors recognize user input and collect data on environment, which is processed and fed back to the user's sensory system. The human body itself is a complex sensor network, where various sensory organs capture environmental information, interact with the nervous system, and transmit it to the brain to support daily life and decision-making processes. Given the multidimensional nature of the human sensory system, wearable devices for the visually impaired should also adopt multichannel sensory interaction. The perceptual memory of visually impaired users is influenced by individual information carrying capacity and the surrounding environment. To reduce their cognitive load, we must consider the information transmission channels and the information carrying capacity of visually impaired users. In the processes of input and feedback, multimodal interaction methods such as voice, short sound effects, and vibration can provide more perceptible input and output options for visually impaired users. Table 1 summarizes the principles of multichannel sensory design, including spatial coincidence, temporal coincidence, the principle of inverse effectiveness, and cross-modal correspondence. Adopting multichannel sensory design methods based on these principles can help mitigate cognitive load issues arising from single-channel information display in wearable devices for the visually impaired, improving the efficiency and comprehensibility of information transmission.

Table 1. Principles Related to Multi- Sensory Design

Theories	Case
Spatial coincidence	When an actor's voice is out of sync with his or her lip movements, it may detract from the viewing experience.
Temporal coincidence	When the position of an object aligns with the direction and distance of its sound source, it aids in accurate localization.
The principle of inverse effectiveness	In dim conditions, relying on sound to gather environmental information.
Cross-modal correspondence	The intensity of visual stimuli may correspond to the loudness of auditory stimuli.

4 BALANCING VISIBILITY AND DESIGN STRATEGIES FOR WEARABLE DEVICES FOR THE VISUALLY IMPAIRED

In the realm of assistive device design and research, the visibility of these devices and their social impact on specific groups, especially the visually impaired, is a critical yet frequently overlooked issue. The visibility of assistive devices shapes public perception of disability. For instance, a white cane improves mobility but makes the disability more apparent, ensuring that some of their needs are acknowledged. However, the stigma associated with assistive technology can also threaten an individual's livelihood and self-esteem.

From both technical and user-oriented perspectives, the functionality, usability, and comfort of wearable devices are essential, but aspects such as emotional engagement, perceptual memory, and social impact between the user and the device are often overlooked. Consequently, many users reject wearable devices that highlight their special status and could lead to discrimination. Research indicates that disabled users consider the visual aesthetics of devices when making choices [6]. Various scholars have suggested strategies to help designers create wearable devices that better cater to the needs of visually impaired individuals. Vaes et al. [7] examined the feasibility of using design approaches to avoid user bias from a social psychology viewpoint, proposing methods such as delabeling and personalization to redefine the product's meaning. Valamanesh et al. [8] emphasized that wearable assistive devices should avoid attracting negative attention to disabilities, and designers should take into account factors like cultural context, wear location, and concealability.

To balance the visibility of wearable devices for the visually impaired and foster user trust, designers must consider aesthetics, customizability, symbolic significance, and age appropriateness. These factors critically influence public perception, whether positive or negative, of the device. However, the existing literature lacks specific design methods. This article synthesizes design methods applicable to wearable devices for the visually impaired, aiming to offer insights for enhancing both theoretical and practical aspects of these devices.

4.1 Addressing User Needs: Participatory Design

Participatory Design is a collaborative approach aimed at developing products and services that better align with user needs and expectations by valuing their explicit and implicit knowledge [9]. Visually impaired individuals are not merely passive recipients of aid; they are active societal participants. Participatory design is vital in creating products for visually impaired users.

Several research teams have successfully employed participatory design methods to understand the needs of visually impaired users. For instance, in the context of social interaction and gaming, Caltenco et al. [10] worked with visually impaired children to explore wearable technology applications, demonstrating that this approach helps identify feedback mechanisms that genuinely suit them. In educational settings, Brule et al. [11] involved visually impaired children and their caregivers in designing a prototype wearable device for geological learning, exploring design opportunities to build geographical knowledge through sensory experiences, thereby opening new avenues for multisensory educational technology.

To better incorporate the perspectives of visually impaired users, researchers have utilized various techniques such as audio diaries [12], scenario construction [13], and tactile paper prototypes [14]. These methods not only boost user involvement and reduce development costs but also help establish a deeper connection with users, enhancing the product's social inclusivity.

4.2 Improving Accessibility: Inclusive Design

Inclusive Design is a bottom-up approach that shares similar but distinct objectives with participatory design: minimizing unconscious exclusion of special users while considering mainstream able-bodied users. Applying an inclusive perspective to the trends and applications of wearable devices can significantly enhance the quality of life for visually impaired individuals and improve social impact and well-being, as measured by user satisfaction and usage rates.

The User Capability and Product Demand framework is a comprehensive analytical tool based on capability needs theory in inclusive design. It evaluates whether product design aligns with users' sensory, cognitive, and motor abilities (Figure 1) [15]. A related concept is the Design Exclusion theory. When the capability demands of wearable devices surpass the actual abilities of visually impaired users, it signifies insufficient inclusivity, leading to design exclusion. For example, touch screen technology, predominantly visually driven, poses challenges for visually impaired users. Therefore, designers must implement additional measures to meet the needs of this group, such as maintaining some physical buttons or incorporating gesture-based functions to mitigate design labeling and ensure an equitable experience.

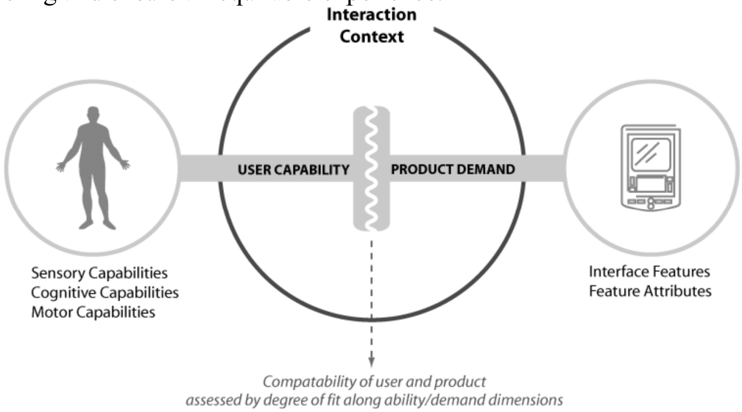

Fig. 1. An illustration of the relationship between user sensory, cognitive and physical capabilities and the demands made on the user by the product [15]

The Inclusive Design Cube is intricately linked to the previously discussed framework. This model assesses the needs of different user groups in a stratified manner, radiating from the center based on variations in user capabilities (Figure 2)[16]. Such a hierarchical approach enables designers to focus not only on the primary target users but also on other potential beneficiaries, such as elderly individuals experiencing vision decline or those with temporary visual impairments. This inclusive design methodology offers an evaluation mechanism using quantifiable metrics, such as user satisfaction surveys or task completion times, to gauge the design's effectiveness.

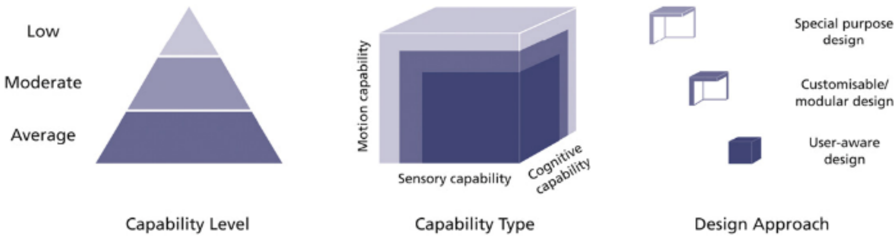

Fig. 2. The Inclusive Design Cube [16]

4.3 Establishing Emotional Connection: Emotional Design

Donald Arthur Norman classifies the emotional system into three levels: visceral, behavioral, and reflective [17]. This idea is closely connected to inclusive design and participatory design, especially when designing wearable devices for visually impaired groups.

Visually impaired individuals have needs that extend beyond material or physiological aspects; they also have higher-level psychological and emotional needs. For instance, a navigation wristband with tactile feedback can not only offer directional guidance but also provide a sense of safety and comfort through warm touch or gentle vibrations, thereby satisfying users' emotional needs.

A design that addresses emotional needs, beyond merely fulfilling basic requirements, can further enhance users' sense of intimacy and social connection, making them feel recognized and respected. This approach aligns with the emphasis on social inclusivity in participatory design. By incorporating emotional design, not only can the acceptance of wearable devices among visually impaired users be increased, but their positive effects on users' emotions and psychological well-being can also be quantitatively assessed through user satisfaction surveys or psychological scales.

5 CONCLUSIONS

As intelligent wearable devices become more prevalent, they increasingly serve as ideal tools for extending individual physical and mental capacities. From data tracking to quantified self and contextual awareness, wearable devices aim to seamlessly integrate with their environment. This trend offers new opportunities for visually impaired individuals to address daily challenges, such as remote appliance control, emergency monitoring, social interaction, and information sharing, thus reducing the digital divide. In terms of fashion integration, advances in flexible electronics and embedded sensors will usher wearable devices into a new cognitive era, meeting aesthetic preferences and boosting the confidence and social skills of visually impaired users. Regarding identity construction and self-expression, wearable devices are not merely tools for augmenting physical abilities; they can dynamically adjust their perception of the world based on tasks, environments, and user characteristics, making them ideal platforms for visually impaired individuals to express themselves.

In conclusion, this paper explores the practical applications and potential value of wearable devices for the visually impaired through theoretical research. Wearable devices hold significant promise in enhancing the interaction between visually impaired individuals and the information environment. Future developments in wearable devices for the visually impaired will involve not only technological innovations but also a holistic approach to social interaction, aesthetic value, and user experience. These trends will provide researchers with a more comprehensive perspective, addressing the inclusiveness gaps in wearable devices and maximizing their value for both individuals and society.

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