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Technology and Analysis of Game Interactivity for People with Disabilities

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Abstract:
With the rapid growth of the digital entertainment industry, game accessibility has become a critical concern for both academia and industry. This paper systematically reviews game interactivity technologies for players with sensory, motor, and cognitive impairments based on research literature from the past five years, including spatial audio, sonification, haptic feedback, eye-tracking, voice control, and dynamic difficulty adjustment. Comparative analysis reveals that these technologies have made significant progress in enhancing immersion and interactivity, but they still face common challenges in calibration complexity, robustness under environmental noise, and real-time performance. The contribution of this paper lies in integrating existing achievements from a cross-disability perspective and proposing future development directions for common issues based on current trends. The research not only provides a theoretical reference for accessible game design but also offers insights for industrial practice and standardization development.

Keywords: Game accessibility; interactive game; artificial intelligence; disability, assistive technology,

1. Introduction

As digital entertainment expands, games have moved beyond leisure to become key media with educational, cultural, and economic value. Globally, the population of active players now surpasses 3.32 billion [1]. However, ensuring equal accessibility to games for all users remains a central challenge. Approximately 22% of the world's population has disabilities [2]. About 66% of disabled players have encountered systemic accessibility issues, such as inconvenient interaction when entering the game environment [3]. This challenge restricts disabled players' engagement and conflicts with the principles of fairness and inclusivity in gaming. In addition, households of disabled people hold over 18 trillion USD in annual spending power [2]. Research further shows that accessible design improves user experience and reduces bias [4]. Thus, studying game interaction technologies for disabled players carries major theoretical, social, and industrial significance.

Traditional game interaction methods (such as keyboards, mice, controller) are not user-friendly for disabled players. To this end, researchers and developers have begun to explore various auxiliary interaction technologies to improve accessibility. The game HaptiCast utilizes Haptic Compensation technology [5],

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which enhances players' immersion in the wizard character through the force feedback of the wand. Eye-tracking technology is developing rapidly, such as Meta released the Aria Gen 2 experimental smart glasses, featuring advanced eye-tracking for gaze tracking, blink recognition, and pupil center estimation, improving human-computer interaction [6]. The global eye-tracking market is forecasted to expand from USD 0.56 billion in 2020 to USD 1.786 billion by 2025, spanning hardware, software, and service domains [7]. The model Polymorph created by Martin et al. [8], utilizes dynamic difficulty adjustment technology to dynamically construct a 2D platform game level, providing a continuous and appropriate game challenge. The Virtual Reality (VR) technology is moving toward multi-sensory integration, such as haptic gloves and full-body feedback systems, to enhance immersion in training and gaming experiences [9].

Although existing research on game interaction technologies for people with disabilities has made some progress, most of it focuses on a single type of disability or a single technology, lacking systematic research across disabilities and technologies. In response to this, we drew on the approach of Emanuele Agrimi et al.'s systematic review on game accessibility for visually impaired players [10]. Reviewing game interaction technologies for people with disabilities using a combination of systematic literature retrieval and analysis methods.

The remainder of the paper is organised as follows. First of all, we will divide the disabled into three types and summary the basic structure of interactive game in Section 2. Secondly, in Section 3, we are going to introduce many typical methods which is help the disabled to play video games. Moreover, Section 4 discusses the challenges and proposes prospects. Finally, Section 5 summarizes this paper.

2. Theories

2.1 Three Types of Disabled People

Before studying the interactive technology for games aimed at people with disabilities, it is necessary to outline the theoretical foundation. According to the World Health Organization, disability is an outcome arising from the interaction between individuals who have health conditions and the surrounding environmental factors. Drawing on the framework discussed in studies [11], we classified players with disabilities into three categories according to the assistive technologies available to address them: sensory, motor, and cognitive.

2.1.1 Sensory impairments

This category primarily refers to visual and hearing impairments. Visually impaired players may face challenges in recognizing game screens, text, or spatial locations, while hearing-impaired players may miss out on essential auditory cues. In games, the auxiliary methods of sensory impairment are mainly realized through sensory substitution, information enhancement and tactile feedback. For example, use subtitles and speech-to-text functions to enhance auditory information [11].

2.1.2 Motor impairments

This category mainly refers to the player's limited motor ability and difficulty in using traditional input devices (such as controllers, keyboards, etc.) smoothly. Their main obstacle in the game is input and control. As a result, accessibility features often focus on helping input, such as voice control systems that translate spoken commands into gameplay actions [11].

2.1.3 Cognitive impairments

This category typically refers to groups with learning difficulties, attention deficits, or limited information processing skills. They encounter obstacles in understanding complex rules, switching between tasks quickly, or maintaining focus. For this group, games often use dynamic difficulty adjustments, simplified operation modes, and intuitive interface design to reduce cognitive burden [11].

2.2 The Basic Structure of Interactive Game

In the process of designing interactive video games, it is essential to follow prescribed structural standards and unified specifications for both design and evaluation. Fundamental Components of Game Interaction mainly involves the medium of video games, elements, design stage and three-level model.

2.2.1 The medium of video games

It mainly consists of console, desktop, mobile phone, handheld console and arcade [12]. Among them, the most popular one is mobile phone, because it can be used to play games anytime and anywhere.

2.2.2 Elements

It is including subject (the player themselves are the main body of experience and interaction.), rules (such as rewards and punishments system, gameplay type and Game difficulty level.), tools (operating equipment, Interactive resources and symbolic language.), division of Labor - The role allocation and collaboration of players in the mission. The community is also an important component; it refers to the virtual society jointly formed by the player community and NPCS [12].

2.2.3 Design stage

First, plan the basic content of the game, then carry out visual design, and finally, through basic programming, realize the basic game operations [12].

2.2.4 Three-level model

Firstly, activity Layer (including worldview, plot, cognition and emotional experience). Secondly, behavior Layer (including rules, task arrangements, and interaction methods). Finally, operation Layer (including interface, input/output, instant feedback). The three layers are not strictly distinguished but interpenetrate each other [12].

3. Classical Technical Approach

In the development of accessible games, several classical technical approaches have emerged to address the diverse needs of players with disabilities. These technologies not only reflect the development of the field of human-computer interaction, but also provide a solid foundation for subsequent research. This section reviews representative technologies based on current business practices and academic research, based on the previous article, categorized into representative technologies for players with sensory, motor, and cognitive impairments.

3.1 Technologies for Sensory Impairments

In order to make up for the lack of perception, there are three main types of assistive technology routes for players with sensory impairments: sensory substitution, information enhancement and haptic feedback. It should be noted that information enhancement techniques are not discussed in detail in this section. The reason lies on that Information enhancement approaches are often closer to design specifications or user experience optimizations (such as captioning, colorblind mode, and contrast adjustments) than cutting-edge technology explorations [11]. Therefore, in the classical technology review, this article mentions it as a background function.

For sensory alternative paths, one major pathway is spatial audio, which allows players to build game worlds without relying on visuals. and 3D sound field technologies rely on head-related transfer functions (HRTF) and higher-order Ambisonics (HOA) frameworks generate three-dimensional soundscapes [13]. This enables visually impaired players to locate the environment with sound. Another major line of work is sonification, which is basically about audio onomatopoeia for in-game elements. The vOICe algorithm, for example, maps pixel positions into frequencies and time, while brightness is encoded as amplitude [14]. More advanced methods, such as the TopoLanguageDepth (TLD) algorithm, combine auditory cues with semantic information, allowing players to not only recognize the presence of objects but also determine their relative depth and position [15].

Haptic feedback systems convert non-tactile information into tactile signals. By varying the frequency, intensity, and duration of vibrations, developers create a mapping between physical stimuli and the meaning of the game. Recent studies have shown that machine learning-based models, such as Long Short-Term Memory (LSTM)-driven classifiers, can convert sound features into semantic haptic patterns, which are then presented through wearable devices [16]. This ensures that important events in the game can be conveyed through touch, expanding the ease of use of immersive experiences.

3.2 Technologies for Motor Impairments

The main challenge that the players with motor impairments face in terms of input and control. Traditional gaming equipment (such as controllers and keyboards) often requires fine physical coordination, which not all players can achieve. Therefore, assistive technologies in this field focus on facilitating alternative input pathways.

The first mainstream help input technology was eye tracking. This technology mainly provides important computer control capabilities for the disabled community through eye contact interaction. Its principle is to calculate the direction of the line of sight by shining an infrared light source on the eye and using the vector formed by the reflection of the pupil and cornea, The positional difference between the two can be used to calculate the user's line of sight direction. This method is called the Pupil Center Corneal Reflection (PCCR) algorithm. Because ordinary visible light cannot provide sufficient contrast, infrared light can clearly distinguish the pupil from the red membrane, ensuring accuracy [17]. According to Tobii, eye and head tracking enable features like aim-at-gaze and extended view, providing gamers with deeper immersion and control by adjusting the in-game camera based on visual attention and natural head movement [18].

The second one is voice control technology, whose principle is based on the voice recognition system of Mel-scale Frequency Cepstral Coefficients (MFCC) and Convolutional Neural Network (CNN). The workflow is from voice collection to feature extraction (MFCC), then to voice classification (CNN), and finally to game command mapping. The process of MFCC feature extraction begins by dividing the speech signal into overlapping frames. Each frame is then multiplied by a Hamming window to reduce spectral leakage, followed by a Fast Fourier Transform (FFT) to compute the power spectrum. Next, the M1 filter bank is applied to extract the Mel spectrum. The filter bank energies are then converted into logarithmic form, and finally, a Discrete Cosine Transform (DCT) is performed to obtain the cepstral coefficients, namely the MFCCs. Users can control the movement direction in the

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game, as well as the start and reset of the game, through the real-time voice commands and recognition system of the game [19].

3.3 Technologies for Cognitive Impairments

Players with cognitive impairment usually have difficulties in understanding rules, processing information, and switching tasks, and assistive technology for this group mainly focuses on optimizing player operations and game dynamics.

Dynamic Difficulty Adjustment (DDA) is a technique that optimizes the player experience by automatically modifying game elements (such as the number of enemies, mission complexity, NPC behavior). A first-person shooter game titled "Cattle Catchers from Outer Space" is designed to explore DDA techniques using performance metrics and emotional responses collected by physiological sensors. It was found that there is no single most effective DDA strategy, and no one method is significantly better than static difficulty settings in enhancing player engagement or gameplay experience [20].

VR technology can also facilitate interaction for individuals with cognitive impairments in certain domains. By employing 3D virtual environments and behavioral interaction techniques to simulate real-life tasks and scenarios, an immersive virtual reality game can be created. Through such games, people with cognitive impairments are able to engage with real-world tasks and contexts in a more effortless and immersive manner, thereby alleviating their cognitive difficulties. This technology represents a significant advancement in the field of rehabilitation medicine [21]. This technology is an extremely important advancement in rehabilitation medicine

4. Discussion

4.1 Challenges

Based on the analysis of the existing barrier-free interaction technologies, the following three challenges can be identified.

First, the calibration challenge represents the most common technical barrier across various technologies. Its work primarily concentrates on visual–tactile or visual–auditory synchrony, the calibration of input–output latency, and the alignment of multiple sensory modalities [22]. For visual–tactile or visual–auditory interactions, the calibration of visual and tactile spatial issues is essential. Poor calibration may lead to perceptual misalignment, reduced usability, and diminished sense of immersion, which represents a central aspect of the calibration challenge. In input–output latency calibration, particularly in the context of haptic feedback, users begin to notice delays once they exceed a certain threshold. This perception of latency often leads to noticeable changes in haptic sensations, resulting in experiences of game stuttering or reduced responsiveness during interaction. The alignment of multiple sensory modalities refers to maintaining temporal and spatial consistency—or sufficient proximity—among different sensory channels such as vision, hearing, and touch in games or interactive systems, so as to ensure that users can integrate this information into a single coherent experience. However, humans have relatively low thresholds for cross-modal temporal delays and spatial misalignments, and exceeding these thresholds can result in perceptual fragmentation. Furthermore, different modalities' hardware—such as haptic devices, speakers, and displays—exhibit inconsistent latency and spatial positioning errors. External environmental factors, including noise, lighting conditions, and wearing configurations, can further amplify these discrepancies

Second, In the field of sensory interaction, the challenge posed by environmental noise to system robustness is an important research direction. In haptic–auditory interactions, vibrations and sounds generated when a tool contacts a surface provide rich information for surface recognition. In practical applications, however, limitations in sensor bandwidth and environmental noise may degrade signal quality, thereby affecting recognition performance [23]. Background noise may interfere with the perception of haptic signals, thereby affecting the user's interaction experience. In haptic interactions, environmental noise may interfere with users' perception, affecting interaction effectiveness and leading to a suboptimal human–computer interaction experience. Studies have also shown that the presence of environmental noise can alter users' perception of haptic feedback [24]. Environmental noise is an inherent technical limitation in human–computer interaction recognition. At present, technologies can be optimized to reduce its interference, but no optimal method exists to completely eliminate the impact of environmental noise.

Third, there is the challenge of real-time performance and latency, which is primarily rooted in calibration issues. Research has shown that network latency affects remote operation systems, as delays can lead to system instability, compromising task supervision and user trust [25]. In this technical limitation, users can also perceive delays in haptic feedback, especially during fine manipulation tasks, where latency exceeding a certain threshold can negatively affect the user experience. Research has shown that when audio leads haptic feedback or vice versa, users can perceive the delay if it exceeds 75 milliseconds or 110 milliseconds, respectively [26]. Tang et al., in their review, pointed out that to achieve realistic haptic experiences, the latency of haptic cues needs to be minimized. They proposed the '1-millisecond challenge,' meaning that the delay between a user's action and the corresponding haptic feedback should be kept within 1 millisecond [27].

4.2 Future prospects

These three types of challenges can sometimes interact with one another, collectively affecting the human-computer interaction experience. While these challenges persist, emerging research points toward promising solutions. One clear trend is the integration of artificial intelligence (AI) into accessible design.

4.2.1 Calibration

Adaptive algorithms can reduce manual setup by learning from player behavior. A calibration-free mobile eye-tracking system realizes automatic calibration without user operation [28]. It consists of an infrared camera, a RGB camera and a front scene camera, which works with deep learning. Evaluations show it achieves low gaze errors, with an average of 1.67°indoors and 1.69°outdoors.

4.2.2 Environmental noise and robustness

AI-driven multimodal fusion can enhance the stability of the system. A place recognition system based on You Only Look Once (YOLO) for object detection and 3D audio feedback demonstrates excellent robustness in occluded scenes [29]. In an environment with 30% occlusion, the system's performance degrades by only 6%, significantly outperforming the baseline model, which suffers a performance drop of 15.5%.

4.2.3 Real-time performance and latency

Efficient machine learning workflows and edge computing solutions are currently being explored. To address the computing power and latency issues in AR games, edge computing technology is used to offload game graphics scene computation from mobile devices to edge servers. This reduces downlink latency by optimizing edge base station allocation and transmission power. Additionally, propose a Multi-Asynchronous-Agent, Loss-Sharing (MALS) reinforcement learning model to solve the asynchronous asymmetry problem, avoiding single-link bottlenecks that slow down the overall performance. Ultimately, the graphic downlink latency and data uplink latency are significantly reduced [30].

5. Conclusion

This study provides a review of game interaction technologies targeting different groups of people with disabilities, based on three classifications of people with disabilities. The results show that technologies such as spatial audio, sonification, haptic feedback, eye-tracking, and dynamic difficulty adjustment provide feasible paths for accessible design. From a cross-barrier perspective, we summarize that there are common challenges in calibration, environmental noise, robustness, and real-time performance and latency. Considering the current trend of AI integration, we propose future research directions for these three aspects. Nevertheless, this work is limited to literature review, and future studies should integrate empirical validation and industrial practice.

Authors Contribution
All the authors contributed equally, and their names were listed in alphabetical order.

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