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Article

Design, Development and Evaluation of a Wearable Haptic Device and a Haptic Digital Maze Game for Children with Visual Impairments

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Abstract: This research examines the development and evaluation of a wearable haptic device and a digital maze game designed for children with visual impairments. The study focused on addressing the specific needs of visually impaired users, employing open-source hardware and software to maintain a low cost while achieving high functionality. The study involves the development of a prototype system and its evaluation through user testing with children with visual impairments. Qualitative and quantitative data were collected to assess usability, accessibility, and overall players' experience, leading to significant recommendations for game improvement. Key findings highlight the potential for two-player adaptation to enhance social interaction, the value of incorporating multiple difficulty levels and varied haptic feedback in maze design, and the critical role of customizable auditory elements in providing individual preferences and sensory understanding. Furthermore, the adaptability of the haptic device for application in various game scenarios beyond the maze, such as virtual boating or urban navigation, demonstrates the broad potential of haptic technology in creating accessible and engaging digital experiences. This research emphasizes the significance of user-centered design principles and the strategic integration of multisensory feedback in creating inclusive and enjoyable digital games for visually impaired children.

Keywords: Haptic Feedback; Wearable Device; Spatial Navigation; Usability; Assistive Technology; Haptic Maze Game

1. Introduction

In recent years, haptics has gained popularity and been widely used in various sectors, such as the augmented reality [1], wearables [2,3], virtual reality [4,5], automotive [6], rehabilitation, cognition, wellness, and mental health [7,8]. It provides users with a sense of touch while using computer applications. It is based on a variety of haptic devices, including 3D mice, gloves, helmets, and vests. These devices simulate the sensation of touching virtual objects or making physical contact with them by applying virtual forces or tactile feedback to the user's hand.

The idea of developing digital games with feedback mechanisms that go beyond visual and audio signals to simulate the sensation of touch between users and virtual objects, whether static or dynamic, through immersive environments has gained popularity in recent years. A convincing interactive experience is still limited by tactile fidelity, even with some impressive advancements in visual and auditory realism [9]. Instead of providing actual tactile feedback, haptic interaction in games is typically more suggestive and symbolic in nature.

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Several haptic-enabled games utilize vibrations, which often do not significantly enhance gameplay mechanics. While some applications of haptic technology prioritize superficial immersion over meaningful interaction or decision-making, its potential to empower individuals with visual impairments is significant.

Haptic feedback offers new ways for environmental interaction and fosters greater independence. For instance, tactile writing systems enable reading,and wearable feedback systems, smart gloves, and haptic maps facilitate independent access to spatial information and navigation. Among the most prominent applications are Braille displays and tactile screens, which allow touch-based reading and writing. Dynamic Braille displays, capable of real-time content updates, offer a considerably more adaptable and practical reading experience [10–12] compared to static systems. This field has advanced to include haptic tablets that utilize raised surfaces or micro-vibrations to represent text, symbols, and basic graphics [2,3].

Wearable haptic technology, including haptic vests and wearable tactile feedback systems, enhances navigation for individuals with visual impairments. These devices utilize tactile mapping and vibration patterns to guide users and signal obstacles, providing a more reliable alternative to relying solely on auditory cues, which can be ineffective in noisy environments [10,13,14]. Consequently, users can maintain better situational awareness in unfamiliar or challenging settings.

Furthermore, haptic technology plays a crucial role in education, particularly for students who are visually impaired. Touch-based learning tools, such as 3D models and tactile maps, improve spatial understanding and facilitate the comprehension of scientific concepts. When integrated into virtual reality simulations, haptic feedback supports experiential learning by facilitating the development of practical skills and the understanding of abstract concepts [15,16].

The present research consists of two main phases. The initial phase involves developing a wearable haptic device using open-source software and hardware. This haptic device employs vibration motors and microcontrollers to simulate haptic feedback. By using the Arduino Uno platform as the central microcontroller, the wearable haptic hat enables direct and cost-effective interaction between the digital maze game and the player. The second phase involves designing a haptic digital maze game using open-source tools. Developed within the Scratch4Arduino environment, this game allows for the control of Arduino hardware through simple visual programming. In this game, players rely solely on vibrations to navigate a virtual maze, with specific vibration patterns indicating interactive elements or obstacles, such as keys that unlock doors leading to the maze's exit.

In addition to being accessible to visually impaired users, this interactive application aims to give users with visual impairments a meaningful and engaging experience. The game and the device are both made available under open-access licenses, which encourage community members to reuse, alter, and enhance them.

Field research involving visually impaired children is used to assess the effectiveness and reliability of the haptic system. To evaluate how participants react to varying degrees of feedback in controlled environments, the research collects data through interviews, as well as biometric and emotional measurements.

2. Literature Review

This chapter provides a comprehensive review of the existing literature relevant to the development of accessible haptic digital games for children with visual impairments. It aims to contextualize the current research by exploring foundational concepts and recent advancements in haptic technology, accessible game design, and the application of open-source hardware and software in assistive technology. By critically engaging with the current academic discourse, this review will identify significant research gaps and articulate the novelty and necessity of the present study.

2.1. Haptic Technology and Accessibility for Visual Impairment

Haptic technology, the science of transmitting information through touch, has emerged as a powerful modality for enhancing human-computer interaction, particularly for individuals with sensory disabilities [17]. While visual and auditory cues dominate most digital interfaces, haptics offers a unique channel for conveying complex information through touch, making it a valuable tool for enhancing accessibility and interaction for individuals with sensory disabilities [18]. For individuals with visual impairments (VI), haptic feedback can serve as a compensatory sensory input, providing crucial information about their environment, facilitating navigation, and enhancing their engagement with digital content [19].

Early applications of haptic technology for VI focused on sensory substitution, aiming to translate visual information into haptic feedback. Examples include haptic displays for exploring graphical information, haptic maps for navigation, and devices that convert visual scenes into vibratory patterns. More recently, research has explored the use of wearable haptic devices, such as vibrotactile belts, sleeves, or armbands, to provide directional cues for indoor and outdoor navigation [20,21]. These systems aim to enhance spatial awareness and independent mobility, offering a non-visual pathway for understanding the surrounding environment.

Despite these advancements, challenges remain in designing haptic systems for VI. Achieving high fidelity in haptic rendering, ensuring the interpretation of complex haptic patterns, and addressing individual differences in haptic sensitivity are ongoing research areas [22–24]. Furthermore, the cost and complexity of many high-fidelity haptic devices often limit their widespread adoption, particularly in educational or personal use contexts [25].

2.2. Digital Games and Accessibility

Digital games play a significant role in the cognitive, social, and emotional development of children, fostering problem-solving skills, creativity, and social interaction [26,27]. However, the majority of mainstream digital games are heavily reliant on visual input, inherently excluding or severely limiting the participation of children with visual impairments. This exclusion can lead to feelings of isolation and missed opportunities for developmental growth [28].

The field of accessible game design seeks to overcome these barriers by creating games that can be enjoyed by individuals with diverse abilities [29,30]. For visually impaired players, this often involves integrating non-visual feedback modalities. Auditory cues, such as spatialized sound effects, music, and voice narration, have traditionally been the primary means of making games accessible to blind players [31]. These auditory elements can convey information about objects, events, and navigation within the game environment.

The integration of haptic feedback into accessible games offers a powerful complementary approach. By providing haptic sensations that correspond to in-game elements (e.g., walls, boundaries, targets, keys, movement), haptic feedback can create a more immersive and intuitive experience, reducing reliance solely on auditory cues and enhancing spatial understanding [32,33]. Research into haptic games for VI has explored various genres, including adventure games, puzzle games, and, notably, maze navigation games, which inherently lend themselves to tactile exploration [32,34]. The challenge lies in designing haptic patterns that are easily interpretable, non-ambiguous, and contribute meaningfully to gameplay without causing cognitive overload [35,36].

2.3. Open-Source Hardware and Software in Assistive Technology

The adoption of open-source hardware (OSH) and open-source software (OSS) has gained considerable momentum in various technological domains, including assistive technology (AT). OSH platforms, such as Arduino and Raspberry Pi, offer significant advantages for AT development due to their low cost, flexibility, and the vibrant global communities that support them [37]. These platforms enable researchers and developers to create custom solutions without incurring high licensing fees or relying on proprietary components, reducing the financial barrier to accessing specialized technology [38] and making AT more affordable and customizable.

In the context of accessible game development, visual programming environments like S4A (Scratch for Arduino) provide an accessible entry point for creating interactive applications that interface with physical hardware. Scratch's drag-and-drop interface simplifies the coding process, making it suitable for educational purposes and rapid prototyping, even for those with limited programming experience [39]. S4A specifically allows Scratch projects to control Arduino boards, enabling the creation of physical computing projects, including haptic feedback systems [40]. This combination offers a powerful and cost-effective toolkit for developing and testing novel AT solutions.

While the benefits of open-source are clear, a key debate revolves around whether low-cost, open-source solutions can truly achieve the high functionality and fidelity often associated with more expensive, proprietary systems. This study aims to contribute to this discourse by evaluating the performance of an open-source-based haptic system in a practical application.

2.4. Research Gap and Study Necessity

Based on the literature review, several critical gaps emerge that underline the necessity and novelty of the present study:

(a) Integrated Low-Cost Haptic Game Development and Evaluation: While individual components (haptic devices, accessible games, open-source platforms) have been explored, there is a limited body of research that comprehensively details the development, implementation, and rigorous user evaluation of a fully integrated, low-cost, open-source haptic digital game specifically designed for children with visual impairments. Many existing haptic solutions are either proprietary, expensive, or focus on adult populations or specific rehabilitation tasks rather than providing holistic game experiences for children [35,36,41,42].

(b) Empirical Evidence on Haptic Interpretation and Navigation in Children with VI: Although the potential of haptic feedback for navigation in VI is recognized, there is a need for more empirical studies that specifically assess how children with visual impairments interpret diverse vibratory patterns as navigational cues within a game context. Understanding their learning processes and the effectiveness of different haptic cues is crucial for optimizing design [23].

(c) User-Centered Design and Multisensory Integration in Open-Source Contexts: While user-centered design (UCD) is advocated in AT, there is a gap in detailed accounts of UCD principles applied to the iterative development of open-source haptic games for VI children, particularly regarding the integration and customizable options for multisensory feedback (haptic and auditory). The spontaneous suggestions from users, as observed in our preliminary findings, highlight the importance of allowing for such customization [29,30].

This study directly addresses these gaps by:

- Developing a novel, low-cost haptic device and maze game using Arduino and S4A.
- Conducting empirical evaluations with children with visual impairments to assess the game's usability, haptic interpretability, and overall effectiveness.
- Providing detailed insights into the design principles for effective haptic feedback and the importance of customizable multisensory experiences based on direct user input.

The literature review demonstrates a clear need for accessible digital games that cater to the unique sensory experiences of children with visual impairments. Haptic technology, when thoughtfully integrated with open-source platforms, offers a promising pathway to achieve this. By addressing the identified research gaps, this study aims to provide valuable empirical evidence and practical guidelines for designing and implementing effective, low-cost, and engaging haptic digital games, ultimately fostering greater inclusion and enriching the developmental experiences of visually impaired children. The findings will not only advance the academic understanding of haptic interaction in accessible gaming but also provide concrete recommendations for future development in this vital area.

Based on the literature review, the present research addresses several questions about haptic interaction for people with VI:

- (a) Can a functional and low-cost wearable haptic device and digital maze game be successfully developed using open-source tools and materials?
- (b) To what extent can children with visual impairments effectively interpret vibratory signals and navigate a virtual maze using the developed haptic system without reliance on visual stimuli?
- (c) Will children be able to interpret vibration signals from the haptic system as navigational feedback, thereby supporting their movement through the game?

Based on the research objectives, the following hypotheses guide the investigation:

Hypothesis 1. *A functional and low-cost wearable haptic device and digital maze game can be successfully developed using open-source tools and materials, demonstrating high functionality despite cost constraints.*

Hypothesis 2. *Children with visual impairments will effectively use the developed haptic device and game to navigate and interact, without the need for visual stimuli.*

Hypothesis 3. *Children will interpret vibration signals from the haptic system as clear navigational feedback, effectively supporting their movement and goal achievement within the game.*

3. Development of Wearable Haptic Device and Haptic Digital Maze Game

This section describes the development process of the wearable haptic device. The development of the haptic feedback system comprises two main parts: (a) a controller and (b) a wearable haptic hat. These two components of the haptic device are functionally connected via a ribbon cable. The individual construction phases are described in detail below.

(a) The controller serves as the primary means of user interaction between users and the digital game environment. It includes a joystick for inputting player actions and four vibration motors that provide haptic feedback in response to user actions. Through the joystick, the player can navigate in two dimensions: horizontally (x-axis) and vertically (y-axis). The four vibration motors function as a mechanism for delivering haptic feedback from the game to the player (**Figure 1**).

Figure 1. The Controller.

(b) The next stage involved constructing the haptic hat and connecting it to the controller, thereby creating a wearable haptic device capable of facilitating player interaction with the game and receiving corresponding haptic feedback. After completing the connections of the four vibration motors, these were strategically placed at four locations on the hat: front, back, left, and right, as shown in **Figure 2**. After final checks to ensure the proper functioning of all components, the construction process of the wearable haptic device was completed.

(c) The digital game entitled "The Labyrinth of Vibrations and the Hat of Senses" was developed with a simple interface, given that it is primarily intended for individuals with visual impairments and relies solely on haptic feedback, without visual stimuli. Consequently, the game was designed in a two-dimensional (2D) environment and includes a limited number of objects (the simultaneous presence of many objects or enemies can confuse due to repetitive haptic feedback). The game is an interactive maze-based experience designed to challenge players through haptic feedback. Players navigate a series of increasingly complex levels, where progress depends on finding and collecting keys to unlock doors. The game integrates haptic feedback to enhance immersion, with vibrations signaling key interactions or obstacles. Unlike traditional games, there is no scoring system; the focus of the game is placed entirely on spatial awareness, exploration, and haptic interaction rather than competition or performance metrics.

Figure 2. The Wearable Haptic Device.

Upon starting the game, an initial screen (**Figure 3**) appears with three options: (a) listening to the game's storyline, (b) familiarizing oneself with the haptic feedback for each different event to prepare for gameplay, and (c) starting the game.

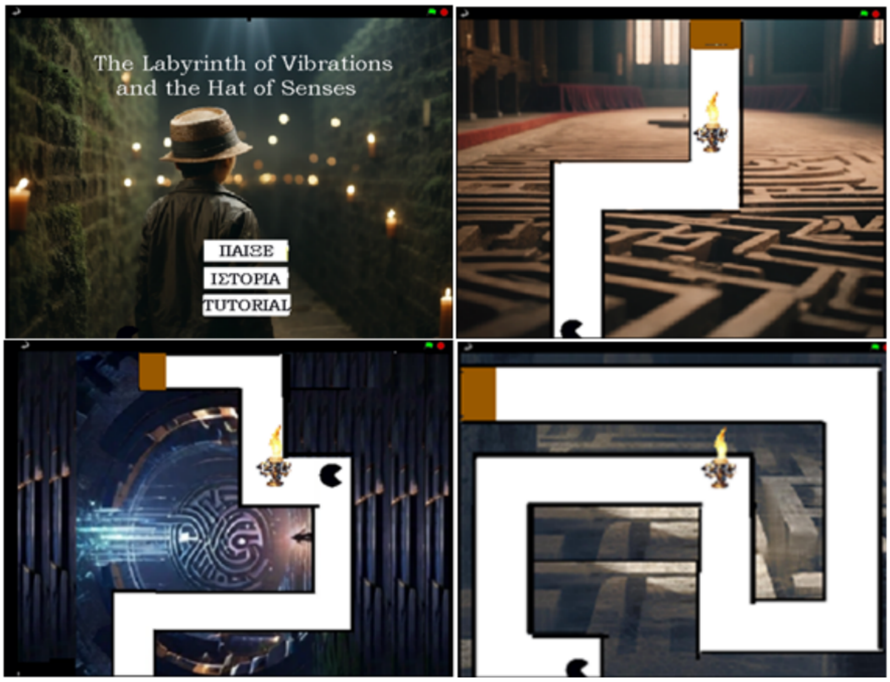

Figure 3. Screenshots highlighting core gameplay elements, including locked doors, collectible keys, and level progression mechanics.

For the development of the game, the visual programming environment of S4A (Scratch for Arduino) was utilized. The process began with the design of the labyrinth layouts directly within S4A. Its intuitive drag-and-drop interface was used to easily define paths, walls, and start and end points. Simultaneously, the haptic feedback logic was programmed [40]. This involved defining specific building blocks (blocks) in S4A to activate distinct vibratory patterns on the haptic headband and the portable device. These patterns corresponded to actions such as player movement, collision with obstacles (left, right, front, back), and achievement of a goal. Finally, continuous iterative testing and improvements were carried out. Initial builds were checked to ensure that the game's sensors accurately read the player's position relative to the walls and that this information was correctly translated into haptic commands. This continuous process of checking and adjustment was fundamental to ensuring the game's functionality and responsiveness.

The game consists of nine levels, each designed to increase in difficulty gradually. Each level presents a maze with a distinct shape that gets increasingly intricate as players progress. Simple, uncomplicated corridors in the early stages help players adjust to the haptic controls and mechanics. The mazes become larger and more complex as the game progresses, necessitating increased focus and thoughtful decision-making. Players are encouraged to plan their route using vibrations and are given a strategic element when they encounter locked doors in certain stages that can only be opened by gathering specific keys.

The simplest way to interact in the game environment is through real-time haptic feedback from vibration motors [43]. The haptic feedback system enhances player immersion through targeted vibrations. A simultaneous vibration from all motors signals the start of each level, while collecting an item triggers two consecutive full-head vibrations. Three rhythmic pulses indicate level completion. Collisions with maze walls activate localized vibrations, which occur in the left, right, front, or back direction, depending on the impact point. These cues provide real-time spatial awareness, guiding player movement and reinforcing actions, while supporting intuitive navigation through the maze environment. Instead of relying on visual or auditory feedback, players can use this haptic language to understand and respond to the game's challenges [44].

The game offers an inclusive setting where players with VI can fully participate and enjoy the experience because it solely relies on haptic interaction. In addition to making the game playable, the careful incorporation of haptic feedback, well-designed levels, and intuitive navigational logic fosters the development of spatial awareness, orientation skills, and strategic thinking. It is a significant step toward more inclusive digital games and a practical example of how technology can lower barriers to participation.

3.1. Haptic Feedback Customization for Personalized Experience

In developing the haptic maze game, we opted to maintain a consistent vibration intensity for all users. This approach ensured predictability, prevented sensory overload, and facilitated faster user familiarization. Information differentiation was achieved through vibration timing and patterns, which were thoroughly explained to players (e.g., a short pattern for an obstacle, a continuous one for a clear path), enabling them to develop a mental "dictionary" of haptic cues.

The strategic placement of vibrators on the haptic headband (left, right, front, back) spatially indicated the presence of obstacles, leveraging the body's innate ability to perceive the direction of a haptic stimulus.

Individual player adaptation was achieved indirectly, not by altering vibration intensity, but by leveraging scientific principles. Neuroplasticity [45] allowed visually impaired children to develop the ability to interpret haptic signals as navigational information. Personalized learning was facilitated through the progressive increase in labyrinth difficulty, enabling each child to learn at their own pace. Clear instructions in the game's "haptic language," reinforced by prior experience with white canes, reduced cognitive load [46]. Finally, the research revealed how each child developed their strategies, demonstrating that the game allowed for a personalized approach to navigation. Thus, effective and individualized haptic feedback utilization was achieved through systematic training, progressive complexity, and the harnessing of the brain's natural learning and neuroplasticity mechanisms [45].

4. Research Methodology

The research aims to examine how effectively the haptic device and the digital maze game can benefit children with visual impairments. It specifically aims to identify any significant challenges or limitations while understanding how the game impacts navigating skills, strategic cognitive processes, and overall user experience.

4.1. Procedure

The implementation stages of the research were as follows:

- (a) Initial Phase (Preparation): Prior to starting the game, participants were engaged in semi-structured interviews to record their prior knowledge regarding navigation in haptic environments and their expectations of the game experience.
- (b) Experimental Use Phase: Participants played the game for a defined period (30–45 minutes). During this phase, data were collected on:
  Their emotional state is recorded and classified through the recording and classification of facial expressions into six basic emotions.
  Stress levels are measured through the recording of heart rate during gameplay.
- (c) Evaluation Phase (Post-Use): After completing the game, participants took part in a semi-structured evaluation interview that included:
  Evaluation of the haptic quality and feedback.
  Questions about navigation experiences (e.g., feelings during navigation, feelings of insecurity or frustration).

4.2. Participants

The present research an experimental study conducted on a group of individuals with visual impairments.

Participants with visual impairments (n = 14) were selected from students at α Special Primary School of Kallithea, Athens, with their level of vision being the sole criterion. Of the total students, 2 were amblyopic and 12 had total blindness. Specifically, the study included 3 second-grade students (with total blindness), 4 fourth-grade students (with total blindness), 4 fifth-grade students (2 with total blindness and 2 with amblyopia), and 3 sixth-grade students (with total blindness) participated in the study. In addition to visual impairments, some students also presented with comorbid conditions such as ADHD, autism, and motor problems.

This school was chosen primarily due to its specialized focus on educating children with visual impairments and its established expertise in providing a supportive learning environment for this specific population. Its role as a leading educational center for the visually impaired provided direct access to our target participant group. It facilitated the necessary ethical approvals and logistical arrangements crucial for an intervention-based study of this nature.

This research adopted a mixed-methods approach, with a strong emphasis on in-depth qualitative data collection (interviews, facial expression analysis, and heart rate analysis) from each participant to gain a deeper understanding of their interaction and experience with the haptic device and game. For this exploratory design within a specialized and vulnerable population, where recruitment is often challenging due to ethical considerations, accessibility, and the relatively small size of the target group, a sample size of 14 allowed for sufficient data saturation in our qualitative analysis and the collection of rich, detailed insights. This aligns with approaches in similar assistive technology research, which focuses on proof-of-concept and user-centered design within specific populations [47,48].

A purposive sampling was used to select participants for this study. This method was ideal for our exploratory and mixed-methods approach, as well as for the specialized target population, children with visual impairments, who are often difficult to access. The goal was to gain in-depth insights into the user experience rather than to generalize findings statistically. Participants were deliberately selected based on predefined inclusion criteria, through our collaboration with the Special Primary School for the Blind of Kallithea. Although purposive sampling limits the extent to which findings can be generalized to the broader population [49], it enabled the collection of in-depth, relevant data critical to evaluating the feasibility and usability of our haptic system [50].

Written informed consent was obtained from the legal guardians or parents of all child participants. This was secured only after receiving full ethical approval from the Research Ethics and Bioethics Committee of the National and Kapodistrian University of Athens, which specifically addressed research involving minors and vulnerable populations. Additionally, formal written permission was granted by the Special Primary School. Crucially, verbal assent was also obtained from each child, ensuring their voluntary participation in an age-appropriate manner. These comprehensive measures ensured the highest ethical standards were maintained throughout the study.

4.3. Data Collection Methods

4.3.1. Interviews

Qualitative interviews were conducted before and after the children used the haptic maze game, aiming to gain an in-depth understanding of their experiences during interaction with the game. Through open-ended questions, the views, emotions, expectations, and challenges faced by children were recorded, along with their overall satisfaction. Additionally, any improvement suggestions that emerged from their responses were analyzed, providing valuable insights for the design of future versions of the game.

4.3.2. Recording of Children's Facial Expressions

To assess children's emotional experience, facial expressions were recorded and analyzed using Noldus FaceReader 4.0, an advanced facial expression recognition software. This tool, utilizing sophisticated machine learning algorithms, objectively identifies six basic emotions (happy, sad, anger, fear, surprise, and disgust) and neutral levels [51]. The analysis of facial expressions provided insights into the participants' overall emotional state and engagement, with increased expressions of fear or tension potentially indicating higher stress levels, and the prevalence of happiness suggesting lower anxiety. FaceReader's accuracy in facial expression recognition has been validated in previous studies (around 88%, with joy showing higher accuracy at 96% and anger lower at 76%). This method offered an objective measure of the children's emotional reactions, contributing to a better understanding of their affective involvement and the game's psychological impact.

A front-facing camera was positioned at face level, approximately 1–1.5 meters from the participant, ensuring a clear and unobstructed view of their face (**Figure 4**). The system recorded participants throughout the entire session, allowing for continuous emotional tracking rather than capturing only specific moments. Ambient lighting was maintained at a consistent and evenly distributed level to minimize shadows and ensure optimal facial recognition accuracy. FaceReader 4.0 was calibrated individually for each participant prior to the session to improve the reliability of emotion detection. Participants were seated in a fixed position to maintain consistent framing and minimize variations in camera angle or facial visibility during gameplay.

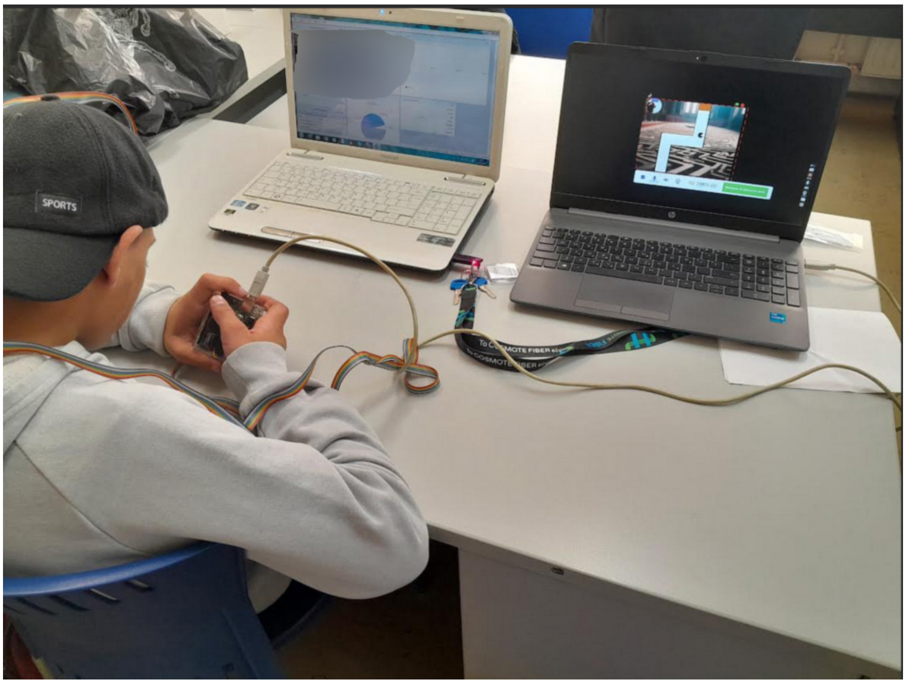

Figure 4. An Illustration of the Research Setup.

4.3.3. Measurement of Children's Heart Rate and Anxiety Level

Physiological data were collected to evaluate the participants' real-time responses using the Xiaomi Redmi Watch 5 Active smart wristband. This device continuously monitored heart rate (beats per minute) and anxiety levels using its advanced sensors. The data were wirelessly transmitted via Bluetooth and stored in the Mi Fitness (Xiaomi Wear) application on a mobile phone, allowing for the analysis of physiological responses during different game phases and the identification of stress or anxiety levels experienced by the children while interacting with the haptic device and game. Heart rate is a recognized physiological indicator of stress, with an increased heart rate often correlating with stressful situations due to activation of the autonomic nervous system. Variations in heart rate during gameplay provided valuable information about the children's psychophysiological state. Significant heart rate increases at specific game moments could suggest heightened anxiety or stress due to task difficulty or goal-oriented pressure. Conversely, a stable or decreased heart rate might indicate lower anxiety levels or greater comfort with the activity. Therefore, real-time heart rate monitoring offered a reliable and objective method for assessing anxiety levels, contributing to a comprehensive understanding of the children's emotional experience and the game's effect on their physiological responses.

4.4. Data Analysis

Qualitative data, derived from interviews with participants, have been analyzed using thematic analysis, following an inductive approach [52]. This involved familiarization with the data, initial coding, searching for themes, reviewing themes, defining and naming themes, and producing the report. This method will enable us to identify recurring patterns, user experiences, and feedback related to the usability and impact of the haptic system. Coding and theme generation were supported by NVivo 15.

Quantitative data, including physiological responses such as facial expressions (captured using Noldus FaceReader 4.0) and heart rate data (collected via the Xiaomi Redmi Watch 5 Active), were analyzed using SPSS Statistics Version 30. A range of statistical tests was employed to examine differences and relationships among participant groups and response variables:

- One-way ANOVA tests were performed to examine statistically significant differences in emotional intensity across various groups based on age, gender, level of visual impairment, presence of comorbidities, and prior experience with digital games. When significant differences were identified, Tukey HSD post hoc tests were conducted to determine which specific group means differed from one another.
- ANOVA was also used to compare mean anxiety levels across different age groups.
- Independent samples t-tests were applied to assess differences in mean anxiety levels between children with and without comorbidities.
- Additional One-Way ANOVA tests were used to evaluate heart rate and anxiety levels at three stages—before, during, and after gameplay—across subgroups defined by age, gender, level of vision loss (total blindness vs. amblyopia), presence of comorbidities, and prior gaming experience.
- Finally, a Spearman's correlation analysis (Spearman's Rho) was conducted to explore the relationship between average emotional intensity and average anxiety levels, the latter being represented by mean heart rate during gameplay.

5. Results

5.1. Children's Perceptions About the Haptic Device and the Maze Game

Initial interviews with children provided valuable insights into their experiences with digital games and other haptic technologies, as well as their expectations for a new game designed to be accessible for individuals with visual impairments. A key finding was the general lack of familiarity with digital games among the participants. Out of the 14 children involved, only three reported any prior experience with such games, typically through the assistance of sighted siblings or via auditory feedback. This variance in prior exposure influenced their initial reactions. While some children expressed enthusiasm and curiosity towards the idea of a game they could play without sight, a smaller number were initially hesitant. However, the concept of a game using a haptic hat irritated their interest and appeared to shift their attitudes positively.

A frequent theme was the central role of the white cane in enhancing spatial awareness and facilitating obstacle detection. When asked how they would navigate an unfamiliar room, the white cane was consistently identified as their primary tool. For those with some experience in digital gaming, the importance of sound and descriptive audio was emphasized. These children appreciated the ability to interact with the game environment, such as driving a car, and found audio feedback essential for understanding in-game actions.

Regarding the haptic hat, most children without previous digital gaming experience expressed interest in trying it. They appeared to intuitively relate the hat's haptic feedback to the white cane's function in detecting obstacles. All participants demonstrated a desire to engage with a game that was primarily operated through touch, although they also acknowledged the challenge of navigating without visual or auditory feedback. Vibrational feedback was widely recognized as potentially very helpful.

These preliminary findings revealed key design principles for accessible gaming for children with visual impairments. Effective design must prioritize haptic feedback, such as vibrations, clear and comprehensible auditory signals describing the game environment, and simple gameplay mechanics. Accessibility relies heavily on intuitive interaction, ease of learning, and minimal reliance on vision. A gradual introduction of new game elements, paired with consistent feedback to the player, was also identified as essential.

Going forward, the design process will focus on integrating these principles into the development of the haptic hat game. Particular attention will be given to the use of sound and vibration to guide players through a maze and alert them to obstacles, ensuring an experience that is both enjoyable and fully accessible.

The final interviews with the children highlighted the diverse expectations they held prior to interacting with the game, revealing the variety in how each child with visual impairment perceives both play and haptic technology. Although several children found the experience differed from their initial expectations, all ultimately described the experience as positive. None of the participants expressed negative feedback, and all characterized the game as fun, suggesting its success in engaging users and generating positive emotions, regardless of their prior assumptions.

Most children perceived the game as easy and enjoyable to use, indicating a high level of usability and practical interpretation of haptic feedback. The use of the haptic hat for navigation proved effective, enhancing their spatial awareness and orientation. While two students experienced isolated difficulties, one felt anxious about using the hat, and another did not grasp the game's objective, these issues did not significantly affect the overall play experience.

Several students expressed a desire for the inclusion of audio elements, reflecting not only the importance of a multisensory experience but also the children's creativity in imagining ways to improve the game. Their suggestions, such as background music, footstep sounds to indicate movement, narration, and audio-based rewards, represent valuable insights for enhancing engagement and immersion. At the same time, the preference of some for a non-sound version of the game highlights the need for customizable audio settings, enabling the experience to be tailored to individual preferences and needs.

Overall, the game successfully evoked primarily positive emotions, including joy, excitement, and satisfaction. The sense of accomplishment from overcoming challenges and active participation further reinforced this positive experience. Although one child reported anxiety linked to the use of the hat, this was an isolated incident that emphasizes the importance of gradual familiarization with new technologies.

Finally, while many children were satisfied with the game as it was, others proposed enhancements, such as additional levels, increased difficulty, narrative guidance, and more multisensory elements, including varied sounds and Braille. These suggestions offer meaningful directions for further development of the game as an inclusive educational tool. By incorporating such feedback, the game can evolve to support greater accessibility, personalization, and broader educational applications.

5.2. Impact on Players' Emotional States

Emotional states during the maze game were assessed using Noldus FaceReader 4.0 software. This advanced facial expression analysis tool that identifies and quantifies the presence of six universally recognized basic emotions: happiness, sadness, anger, surprise, fear, and disgust. This method allowed for an objective, real-time evaluation of the children's emotional responses during gameplay, providing valuable insights into how children with visual impairments emotionally engage with interactive and sensory learning experiences. The software operates by analyzing facial muscle movements and expressions captured via video, translating them into emotion scores expressed as percentages. These scores reflect the intensity and frequency with which the children expressed each emotion throughout the duration of the activity.

The findings from the emotional data revealed a clear predominance of positive affective responses (**Figure 5**). Among the six emotions analyzed, "surprised" was the most frequently and strongly expressed, with an average intensity of 13.99%. This was closely followed by "happy," which was recorded at an average of 12.87%. These two emotions suggest a high level of engagement, curiosity, and enjoyment during the game. Surprised, in particular, often indicates cognitive stimulation and attentiveness, while happiness is strongly linked to enjoyment, comfort, and a sense of reward. Together, these emotional markers support the conclusion that the game positively engaged the children and likely found the experience novel and enjoyable.

In contrast, negative emotional expressions, including anger, fear, disgust, and sadness, were generally recorded at much lower average levels. This pattern reinforces the notion that the game environment was perceived as safe, engaging, and emotionally supportive. Such low levels of negative effect suggest that the haptic activity did not provoke distress, frustration, or fear, which is especially important when designing educational interventions for children with disabilities who may be more sensitive to overstimulation or unfamiliar environments. Among the negative emotions, sadness was the only one that showed a statistically significant difference in expression across different age groups (p = 0.040). This suggests that age may play a role in how children express or process sadness in response to a novel stimulus. However, when a Tukey Significant Difference (HSD) post-hoc test was applied to determine exactly which age groups differed from each other, no specific pairwise comparisons reached statistical significance. This is likely due to the small sample sizes in each age group, which reduces the statistical power of the analysis and makes it difficult to detect subtle group differences.

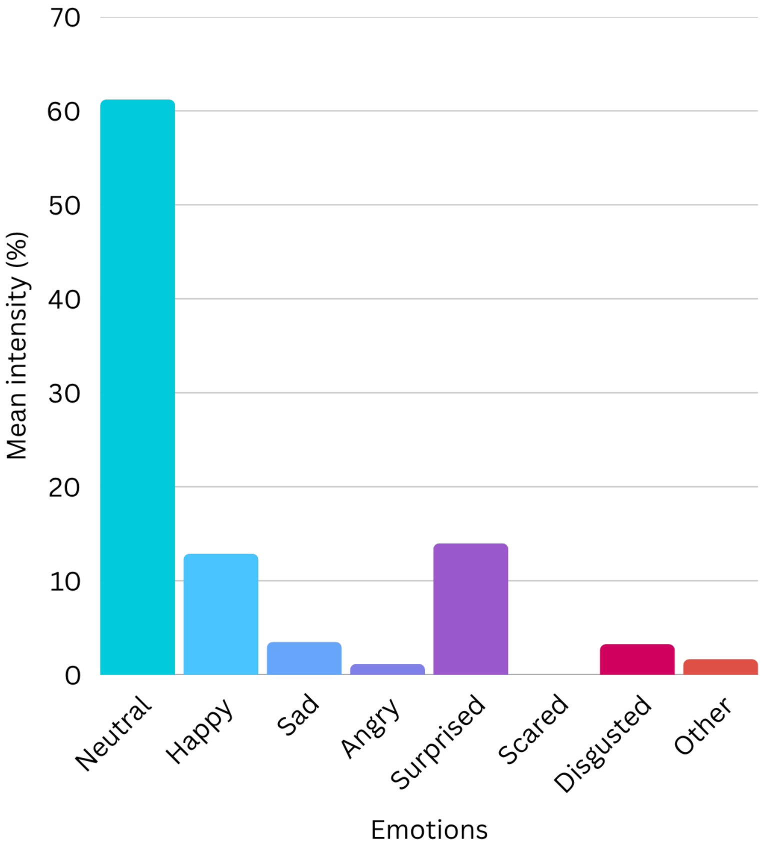

Figure 5. Average Emotion Intensity During the Game.

Note: "Other" means that no emotion was recognized.

Further statistical analyses using One-Way ANOVA were conducted to assess whether emotional intensity varied significantly across several independent variables, including gender, age, level of visual impairment (e.g., total blindness vs partial sight), presence of comorbidities (such as autism, ADHD, or physical disabilities), and previous experience with similar types of games. In all these cases, except for sadness and age, no significant differences were observed (**Table 1**).

Table 1. ANOVA Significance Summary Matrix for Emotions.

Emotion	Age	Gender	Vision Level	Comorbidities	Prior Experience
Neutral	NS*	NS	-	-	-
Happy	NS	NS	NS	NS	NS
Sad	p = 0.040**	NS	NS	NS	NS
Angy	NS	NS	NS	NS	NS
Surprised	NS	NS	NS	NS	NS
Scared	NS	NS	NS	NS	NS
Disgusted	NS	NS	NS	NS	NS

Note: * NS indicates that no statistically significant difference was found; ** Statistically significant difference.

This suggests that the children responded to the haptic game in similar emotional ways, regardless of their backgrounds or characteristics. The absence of strong group effects supports the idea that well-designed sensory educational tools can be inclusive and universally engaging for children with diverse visual impairments and cognitive profiles.

The overall implication of these findings is that haptic games, when designed thoughtfully and implemented in a supportive environment, can foster positive emotional engagement across diverse groups of children with visual impairments. Positive emotional responses are crucial for learning, motivation, and memory, especially in populations that may experience greater educational or social challenges. By eliciting emotions such as surprise and happiness, these types of games can help create an enriching learning atmosphere that promotes both cognitive and emotional development.

However, while the findings are promising, the study also highlights a critical limitation: the small sample size, particularly when analyzed by subgroups. This limitation likely prevented the detection of more differences between groups and limits the generalizability of the results. As a result, the researcher emphasizes the importance of conducting follow-up studies with larger and more diverse samples to validate the findings and explore in greater depth how emotional responses during haptic gameplay might vary with demographic and clinical characteristics. Expanding the sample size would also allow for more robust statistical analysis, potentially revealing additional relationships between emotional expression and factors such as developmental stage, level of support needs, or previous exposure to multisensory environments.

In conclusion, the use of facial emotion recognition technology revealed that children with visual impairments responded positively and with emotional engagement to the haptic maze game. High levels of surprise and happiness, combined with minimal expression of negative emotions, indicate that such activities can be emotionally rewarding and accessible. Despite the limited sample size and the inability to confirm specific group differences, the results offer valuable insights into the emotional impact of sensory play and point toward the potential for broader application of such interventions in inclusive education settings.

5.3. Impact on Heart Rate and Stress Level

The physiological variable measured was heart rate (in beats per minute) and stress level. Data were collected at three time points: before, during, and after the gameplay experience. Statistics showed a slight increase in both mean heart rate and stress levels during the game, with heart rate remaining elevated even after the game ended, while stress levels returned closer to baseline.

The mean heart rate increased from 83 bpm before the game to 84.79 bpm during the game, and then to 85 bpm after. Similarly, the average stress level rose from 36.14 to 37.93 during the game and then slightly decreased to 37.43 afterward. While these differences were minor, they reflect an expected physiological response to engagement and stimulation during interactive tasks. A more detailed descriptive analysis (including median, standard deviation, and range) reinforced this trend, with relatively small standard deviations indicating that the changes were consistent across participants (**Figure 6**).

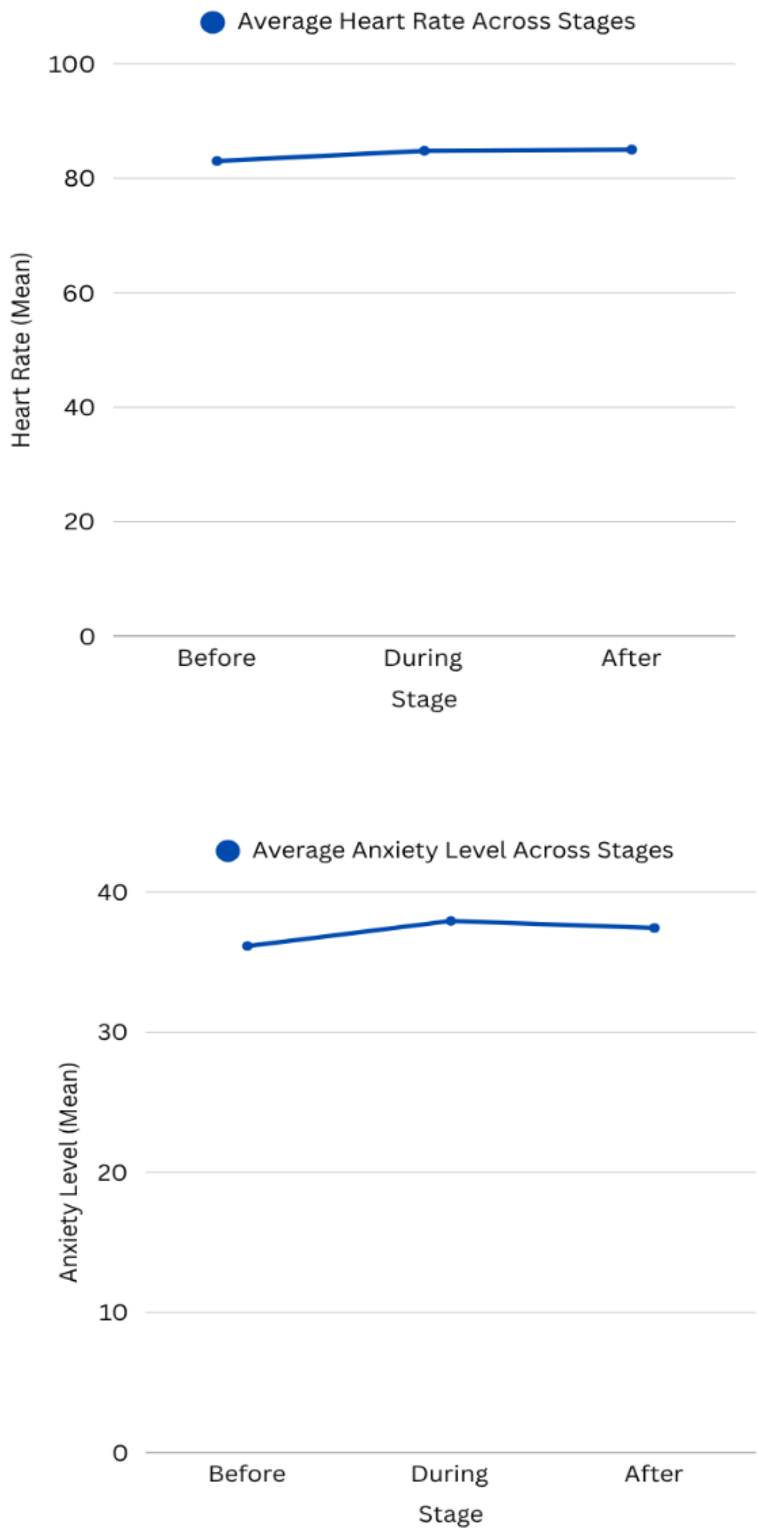

Figure 6. Average Heart Rate and Anxiety Level Across Stages.

To assess whether specific variables influenced these psychological changes, the study employed a series of

One-Way ANOVA tests. These analyses examined whether gender, age, level of vision impairment (total blindness vs amblyopia), presence of comorbidities (such as ADHD, autism, or physical paralysis), and prior experience with similar games had a statistically significant impact on heart rate and stress levels. The findings showed no significant effects of gender, age, visual impairment, or prior experience on heart rate or stress at any of the three stages. This suggests that, regardless of these demographic or experiential factors, the game evoked similar levels of arousal and stress.

However, the presence of comorbidities did show a statistically significant effect on pre-game stress levels (p = 0.038). Children with additional diagnoses such as ADHD, autism, or physical impairments reported higher baseline stress, which implies that such conditions may predispose children to heightened anxiety in unfamiliar or stimulating settings. Although not all differences were statistically significant, there was a clear tendency for children with comorbidities to exhibit higher physiological responses throughout the activity (**Table 2**).

Table 2. Significance of ANOVA Results Across Variables.

Variable	Heart Rate (Before)	Heart Rate (During)	Heart Rate (After)	Anxiety (Before)	Anxiety (During)	Anxiety (After)
Gender	NS	NS	NS	NS	NS	NS
Age	NS	NS	NS	NS	NS	NS
Visual Impairment	NS	NS	NS	NS	NS	NS
Prior Experience	NS	NS	NS	NS	NS	NS
Comorbidities	NS	NS	NS	(0.038)*	NS	NS

Note: * Statistically significant difference.

The study also examined potential relationships between emotional responses and stress levels using Spearman's rank correlation (Spearman's rho). This non-parametric test was used to investigate whether specific emotions, as reported by the participants, were correlated with changes in heart rate during gameplay. A strong and statistically significant negative correlation was found between the emotion of joy and the change in heart rate during the activity (ρ = –1.000, p = 0.014). This suggests that when children experienced happiness, their heart rates were less likely to increase significantly, indicating lower stress levels. On the other hand, a marginally significant positive correlation was observed between sadness and heart rate change (ρ = 0.575, p = 0.050), implying that children who felt sad during the game were more likely to experience heightened physiological arousal (**Table 3**).

Table 3. Spearman's Rank Correlation.

Emotion	Correlation Type	Coefficient (ρ)	P-value	Interpretation
Happy	Negative Correlation	–1.000	0.014*	Strongly associated with decreased stress.
Sad	Positive Correlation	0.575	0.050	Marginally associated with increased stress.

Note: * Statistically significant correlation.

These findings are crucial for understanding the emotional and physiological impact of interactive haptic experiences on children with visual impairments. The slight increase in stress and heart rate during the game is likely a natural response to novelty, stimulation, and cognitive engagement. Significantly, the lack of significant differences based on most demographic and experience-based factors suggests that such activities can be universally engaging and suitable for diverse groups of children with visual disabilities. Moreover, the observed correlations between specific emotions and physiological responses underline the importance of fostering positive emotional experiences during educational play. When children felt happiness, their stress response diminished, highlighting the potential of well-designed sensory games to promote emotional well-being.

In conclusion, while the haptic game caused only modest changes in heart rate and stress levels, these changes were not significantly influenced by gender, age, or vision level. However, comorbidities played a role in baseline anxiety levels, and emotional states, particularly joy and sadness, were meaningfully associated with physiological responses. These results suggest that haptic, emotion-driven educational tools can be beneficial in managing stress and promoting emotional regulation, especially for children with visual impairments and additional needs. Future research could further explore how different types of sensory stimuli and emotional triggers affect stress and engagement, potentially contributing to the development of more inclusive and therapeutic educational interventions.

6. Discussion

This research explores the development of haptic digital games for children with visual impairments, focusing on the use of wearable haptic devices and haptic feedback as primary means of interaction and navigation. The research endeavor began with a broader idea of integrating haptic technology into digital games for sighted individuals. However, a systematic literature review led to a more specialized focus on the needs and capabilities of individuals with visual disabilities. This shift proved pivotal, allowing for a concentration on critical accessibility issues and the investigation of innovative solutions for the entertainment and education of this user group.

The research was structured around three fundamental research hypotheses. The first hypothesis examined the feasibility of developing a wearable haptic device and a haptic digital maze game using open-source software and hardware, while maintaining low cost and achieving high functionality. In agreement with prior findings, the analysis confirmed the availability of mature and flexible open-source hardware platforms, such as Arduino, which provide a wide array of options for developing affordable and customizable haptic devices [37,40]. Such platforms allow researchers and developers to create tailored solutions without the burden of high licensing costs or dependence on proprietary components, thereby lowering the financial barriers to accessing specialized technology [38] and promoting the development of more accessible and adaptable assistive technologies (AT).

The support of a large community and the availability of various sensors and actuators enable the implementation of satisfactory haptic feedback at a comparatively low cost. Furthermore, the use of open-source game development environments, such as S4A, in conjunction with these platforms, provides the necessary tools for creating digital games with integrated haptic feedback. The choice of open-source software and hardware contributed to a significant reduction in development costs, with the primary cost focused on the procurement of physical components and development work. However, achieving high functionality required careful material selection, intelligent design, and effective hardware-software integration, cautioning against the risk of degrading the user experience by overemphasizing low cost.

The second research hypothesis focused on the ability of children with visual impairments to effectively use the device and the game without requiring visual stimuli. The quantitative and qualitative data from the research provided strong support for this hypothesis. Despite the majority of participants having no prior experience with digital games, all children managed to interact successfully with the game. The initial reservation expressed by some children towards unfamiliar technology was quickly overcome through direct contact with an environment that did not require visual information. The positive evaluation of the experience by all children, with descriptions such as “fun,” “enjoyable,” and “easy to use,” demonstrated the game’s acceptance and practical accessibility. Previous studies have supported the hypothesis that vibration-based cues can serve as practical tools for guidance and navigation, particularly for children with visual impairments. These studies highlight how such cues are not only accessible but also intuitively interpreted and utilized by the children [31,41]. Consistent with findings from other researchers, the children’s spontaneous interest in adding auditory elements to the game further emphasized both their adaptability in functioning without sight and the importance of incorporating multisensory design approaches [10,53].

The third research hypothesis examined the ability of children to interpret vibrations as directional feedback for their navigation. The research findings fully confirmed this hypothesis. The children not only responded positively to the use of the vibratory mechanism but also utilized the vibrations as essential directional feedback for navigating the game’s virtual world. The effectiveness of vibratory guidance as a sensory aid, enabling children to perceive and follow paths and complete mission objectives, is supported by findings in prior studies [22–24]. Children’s prior experience with the white cane appeared to facilitate the transition to interpreting vibrations as a means of navigation. The successful completion of the missions by the majority of children demonstrated the effectiveness of the vibratory system as a guidance mechanism. At the same time, the few difficulties encountered were temporary and addressable with support and practice.

Overall, the research revealed the feasibility and effectiveness of developing accessible haptic digital games for children with visual impairments using open-source software and hardware. The findings highlight the importance of carefully designing haptic feedback, integrating multisensory elements, and the leveraging of pre-existing sensory experiences to create effective and enjoyable interactive experiences. The research paves the way for further exploration and development of innovative solutions in the entertainment, education, and socialization of individuals with visual disabilities in the digital world.

7. Conclusions

This study examined the usability, emotional impact, and physiological responses associated with a haptic maze game developed for children with visual impairments. The results indicated that the game was well-received by most participants, who found it enjoyable, easy to use, and accessible regardless of their prior experience with digital games. The haptic hat used for navigation was intuitively understood by the children, many of whom likened its functionality to that of the white cane, which they commonly use for spatial orientation. Even participants unfamiliar with digital gaming quickly adapted to the new format, demonstrating the game's accessibility and user-friendliness.

In terms of emotional impact, the analysis revealed that the game predominantly elicited positive emotions. The most frequently observed emotions were surprise and happiness, indicating high levels of engagement, curiosity, and enjoyment. Negative emotional responses—such as anger, fear, sadness, and disgust—were minimal across the participant group, suggesting that the game environment was perceived as emotionally safe and supportive. Notably, emotional responses were consistent across different demographic and clinical subgroups, such as age, gender, degree of visual impairment, and prior gaming experience. This highlights the inclusive nature of the game's design and its potential for broad applicability among children with diverse backgrounds.

Physiological data, including heart rate and stress levels, showed only slight increases during gameplay, which are consistent with expected responses to cognitive and sensory stimulation. Although these changes were modest, they reflected consistent level of engagement. Interestingly, the presence of comorbidities such as ADHD or autism was associated with higher baseline stress levels, suggesting that children with additional diagnoses may experience heightened anxiety in unfamiliar or stimulating settings. However, the general trend across participants pointed to stable physiological responses, further supporting the game's suitability for a wide range of users. Furthermore, a strong negative correlation was found between the emotion of joy and heart rate changes, indicating that positive emotional experiences may contribute to stress regulation during gameplay.

The analysis of the research data yielded significant recommendations for improving the game, which can be considered best practices for the future development of accessible haptic digital games for this user group. These practices center on:

(a) The game can be adapted to support two players, a crucial feature that enhances the social dimension and provides a more interactive and enjoyable experience for visually impaired individuals. The addition of two controllers and two haptic hats enables simultaneous participation, allowing for independent navigation and interaction for each player, while the haptic feedback facilitates spatial awareness and in-game actions. This upgrade fosters inclusion, offers opportunities for competitive or cooperative gameplay, and enhances the educational and recreational value by encouraging collaboration and social interaction.

(b) Incorporating additional levels significantly enhances the game's duration, difficulty, and overall player experience. New levels introduce greater depth and continuous challenges, preventing monotony and sustaining players' interest over time. Designed with increasing difficulty and complexity, these levels support continuous practice and skill improvement, adapting to the user's abilities and offering a balanced experience of challenge and reward. For visually impaired users, these additional tracks can vary not only spatially but also haptically, enhancing the perception of progress and variety, increasing replayability, and allowing for different scenarios, objectives, and cooperative elements, making the game more adaptable for individual and educational or therapeutic use.

(c) The expressed desire for auditory elements (music, footsteps, narration, rewards) highlights the importance of a multisensory experience for increased engagement and creativity in game improvement. However, the preference for silience underscores the need for personalization. Therefore, integrating on/off sound options is critical. Adding sounds can enrich the experience by creating atmosphere, enhancing the perception of movement, and providing additional information and reinforcement. Simultaneously, the ability to disable sounds respects individual preferences and needs, such as sound sensitivity or a preference for focusing solely on haptic feedback. The inclusion of controllable audio is a fundamental design principle for accessibility and customization, allowing each player to tailor their experience and enhance enjoyment and game effectiveness.

(d) The wearable haptic hat and the controller possess a wide range of applications beyond the maze game. The same basic device, capable of providing vibrotactile feedback, can be utilized to create a diverse range of interactive experiences. For instance, players could navigate the player into an urban environment guided by vibrations towards specific shops or services, with varying vibration patterns indicating proximity or the type of destination. Alternatively, players could navigate a virtual boat, with vibrations indicating wind direction or water obstacles, while the haptic hat simulates the sensation of oars or waves. This versatility allows for the development of rich and varied games while maintaining the low cost of the basic hardware. Changing the game primarily involves modifying the software and haptic signals, opening new horizons for entertainment and education through haptic interaction. This is particularly promising for creating accessible games for visually impaired individuals, offering diverse and engaging alternatives.

Overall, the study suggests that the haptic maze game successfully promoted emotional engagement, cognitive stimulation, and stress regulation among children with visual impairments. The overwhelmingly positive feedback, combined with minimal negative emotional or physiological responses, points to the potential of such technologies as inclusive educational tools. The game not only provided entertainment but also supported developmental objectives such as spatial awareness and emotional regulation.

Despite these promising results, the study was limited by its small sample size, which may have reduced the ability to detect subtle differences between subgroups. Therefore, future research should prioritize expanding the sample size to include a more diverse group of participants. Additionally, incorporating a control group using traditional game interfaces, either without haptic feedback or relying solely on visual and auditory cues, would strengthen the study design by enabling more precise comparisons. Furthermore, pre- and post-testing assessments should be implemented to measure changes in performance metrics such as maze completion times, error rates, and cognitive mapping skills. Moreover, combining objective data (e.g., task efficiency and error rates) with subjective user feedback through validated tools would provide a more comprehensive understanding of user experience. Future studies should also detail the calibration of haptic feedback, including adjustments to strength, timing, and placement, and explore user-customizable settings. Likewise, longitudinal testing over multiple sessions would help assess learning effects, habituation, and potential fatigue. Meanwhile, randomization and counterbalancing of task order and feedback types would control for order effects and enhance the reliability of the results.

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Institutional Review Board Statement

The study was conducted in accordance with the Declaration of Helsinki and approved by the Research Ethics and Bioethics Committee of the National and Kapodistrian University of Athens (protocol code 37955 and 9/4/2025).

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

Data is unavailable due to privacy or ethical restrictions.

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Conflicts of Interest

The authors declares that they have no conflict of interest.

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