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The Usability of Augmented Reality Applications for Visually Impaired Individuals: A Systematic Review

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ABSTRACT

This paper explores the usability of Augmented Reality (AR) applications specifically designed for visually impaired individuals, focusing on how these technologies can enhance their accessibility and daily living. AR offers potential benefits in areas such as navigation, object recognition, environmental awareness, education, social interaction, and entertainment. However, visually impaired users face significant challenges, including complex interfaces, reliance on visual cues, and limited access to assistive technologies. This paper identifies key usability guidelines to address these challenges, such as ensuring compatibility with assistive technologies like screen readers, maintaining consistency in design, providing clear and accessible user interfaces, and integrating alternative sensory cues like audio and haptic feedback. Furthermore, customization options, collision detection, contextual information, and user-centered design principles are emphasized to enhance the AR experience. The study concludes that incorporating these usability guidelines is crucial for creating AR applications that are intuitive, effective, and tailored to the unique needs of visually impaired users. Continuous user testing and feedback are also vital to further refine these technologies and ensure their accessibility.

***Keywords*— Usability, blind people, visually impaired individuals, AR, Augmented reality**

1. Introduction

Augmented reality (AR) is a technology that overlays digital information, such as images, videos, or 3D models, onto the real-world environment. It enhances the user's perception of reality by blending virtual elements with the physical world. AR can be experienced through various devices, including smartphones, tablets, smart glasses, or headsets.

For visually impaired individuals, AR has the potential to provide valuable assistance and enhance their daily lives in several ways including navigation and wayfinding [1-5], object recognition and identification [6-8], environmental awareness [9], education and learning [5], social interaction [10], entertainment and recreation [11], and text recognition [12].

AR can offer real-time audio or haptic feedback to guide visually impaired users navigating unfamiliar environments. It can provide step-by-step directions, highlight obstacles, and offer contextual information about nearby points of interest. It also, can help visually impaired users recognize and identify objects in their surroundings. Using computer vision algorithms, AR applications can detect and provide audio or tactile feedback about objects, such as identifying currency notes, reading labels, or recognizing faces [13].

AR applications can further provide contextual information about the environment, such as identifying landmarks, describing scenes, or providing information about nearby buildings or public transportation options. This can help visually impaired individuals better understand their surroundings and make informed decisions [2].

Visually impaired students can benefit from AR for educational purposes too. It can provide interactive and immersive experiences, allowing them to explore and understand complex concepts through audio, tactile, or haptic feedback [14].

Moreover, AR can facilitate social interactions for visually impaired individuals by providing real-time information about people nearby, such as their names, interests, or shared connections. This can

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help in initiating conversations and fostering social connections. Besides, AR applications can offer visually impaired users, opportunities for entertainment and recreation. It can enable them to participate in interactive games, experience virtual tours, or engage in immersive storytelling experiences [15].

This research aims to investigate the usability of augmented reality (AR) applications specifically designed for individuals with visual impairments. With the advancements in AR technology, there is an increasing opportunity to create applications that can offer real-time assistance, navigation support, and access to information for visually impaired individuals. This study will assess the current state of AR applications for the visually impaired, discuss the potential impact of these applications on the daily lives of visually impaired individuals, and analyze the challenges and opportunities in terms of usability. By comprehending the usability of AR applications for the visually impaired, we can identify areas for improvement and contribute to the development of more effective and accessible technologies for this community.

Examining the usability of AR applications for visually impaired individuals is crucial as it has the potential to greatly improve their independence, mobility, and overall quality of life. It can encourage their inclusion and participation in various aspects of daily life, including navigating public spaces, accessing information in educational or professional activities, and engaging in recreational events. By comprehending and enhancing the usability of these applications, developers and researchers can ensure that the features and functionalities are specifically designed to meet the distinct needs, preferences, and abilities of users with visual impairments.

2. Methodology

This study follows a systematic approach, reviewing and analyzing the most recent and relevant literature on augmented reality (AR) applications designed for visually impaired individuals. To accomplish the objectives of this paper, we initiated the process by identifying and selecting the most recent and relevant research papers in the augmented reality (AR) field for visually impaired users.

We used a combination of keywords, including "augmented reality," "AR applications," "visually impaired," "blind individuals," "usability," and "assistive technology." These keywords were chosen to ensure the inclusion of papers focused on AR applications in enhancing the usability of visually impaired users.

We searched IEEE Xplore, Google Scholar, PubMed, and ScienceDirect to gather the most relevant articles, as they comprehensively cover technical and assistive technologies. Our focus was on English papers mostly published within the last 10 years in peer-reviewed journal articles, conference papers, and relevant review articles focusing on the usability of AR for visually impaired individuals. Studies that primarily discussed AR for general users without any specific consideration for visual impairments were excluded. No paper was found to report on the subject of this paper in Persian.

Once we compiled this selection, we conducted a comprehensive review of each chosen paper. During this review process, we analyzed and evaluated the content of each paper, paying particular attention to the approach taken to enhance the usability of AR applications for individuals with visual impairments.

Our examination focused on how they aimed to improve the overall user experience for visually impaired individuals when interacting with AR technology. This included studying the specific considerations for usability, design principles, and user-centered approaches that were implemented or proposed within each paper.

3. Enhancing Accessibility for the Visually Impaired through Augmented Reality

In recent years, the development of augmented reality (AR) applications has made significant steps in meeting the needs of individuals with visual impairments. These applications offer promising solutions to a variety of challenges faced by those with visual impairments, such as navigating unfamiliar surroundings[1-5], identifying objects [6-8], and accessing visual information.

The potential of AR technology for this community is vast and has the potential to greatly enhance accessibility, independence, and interaction within the physical environment. As the technology continues to advance, there is tremendous potential for even greater improvements and expansion of AR applications to better serve the diverse needs of this population. The vast potential of AR technology for individuals with visual impairments holds immense promise in improving accessibility, independence, and interaction with their surroundings [16]. As technology advances, there is an exciting opportunity to expand and enhance AR applications to cater to the diverse preferences and needs of those with visual impairments. This progress will greatly promote inclusivity and independence, ultimately enriching their daily lives in numerous facets.

Recent studies and advancements in AR technology have been devoted to tackling the specific barriers encountered by the visually impaired community. These efforts strive to provide creative solutions that empower these individuals and improve their ability to navigate independently. Some noteworthy areas of exploration and growth in this domain can be categorized as follows.

3.1. Object Recognition and Environmental Awareness

This group of studies focuses on helping users recognize objects and understand their environment. Numerous studies have delved into the integration of computer vision and machine learning techniques to facilitate AR experiences that can instantly identify and describe objects through audio. These activities try to enhance the precision and efficiency of object recognition, as well as the authenticity and comprehensibility of the accompanying audio descriptions [6-8].

Yu and his colleagues [7] describe the development of a mobile application designed to assist visually impaired individuals by identifying objects through marker-less AR detection. The application uses a smartphone camera to scan objects and provides audio feedback with the object's name. The system was developed using Unity 3D and the Vuforia SDK to create a dataset of 40 objects. Testing was conducted to assess the application's ability to detect and identify objects, and the app successfully recognized predefined objects within a few seconds. Mambu and colleagues also designed and developed a mobile-based application called "Blind Reader," for object identification using augmented reality (AR) to assist visually impaired users. The application utilizes markerless detection technology, allowing users to aim their camera at an object, which is then matched with a pre-stored dataset. This system was validated by observing its ability to correctly detect objects and by measuring the time required to provide audio feedback [8].

3.2. Navigation and Wayfinding

The advancements in AR technology have been focused on enhancing navigation capabilities with features such as audible cues, enhanced spatial awareness, and interactive guidance. This encompasses various studies on indoor navigation systems, solutions for outdoor wayfinding, and the incorporation of location-based services to aid those with visual impairments in efficiently navigating their surroundings. By overlaying digital information onto the physical environment, AR can offer personalized guidance, identify points of interest, and provide spatial orientation, thereby improving mobility and independence [1-5]

In a research [1], a mobile application was designed and implemented to help visually impaired individuals navigate indoor spaces using Augmented Reality (AR) and rMQR codes. The application scans rMQR codes placed at various locations indoors and plays corresponding audio descriptions to guide users. rMQR codes were chosen for their compact design and higher information storage capacity compared to traditional QR codes. These codes were placed at strategic points of interest in academic spaces, like bathrooms and libraries, where they could be easily scanned. The codes contain information about the space and its surroundings, enhancing users' orientation and mobility. The app was developed using Unity and Vuforia The audio descriptions were generated using NaturalReader, which provided relevant information about the space, such as its features and layout. The system was designed to accurately detect codes at different angles and provide timely, clear audio descriptions. Optimal performance was found when scanning codes at a distance of 1-2 meters, and the code size used was 2x15 cm. Thirty-six students were involved in a validation phase where they tested the app while wearing sleep masks to simulate visual impairment. The project showed hopeful results in enabling visually impaired users to navigate indoor spaces more effectively.

Another research [2] presents the development and enhancement of a system called ARIANNA+ for supporting visually impaired individuals with autonomous navigation, both indoors and outdoors. This system is an extension of the ARIANNA platform, which was initially built for visually impaired people to navigate environments using QR codes and physical pathways (painted lines, tactile pavements, etc.). ARIANNA+ eliminates the need for physical modifications to the environment (such as placing lines on the floor) by using Augmented Reality (AR) technology. ARIANNA+ incorporates machine learning and CNNs to recognize objects and buildings, providing additional context and interaction with the environment. This new feature allows users to access digital content related to specific points of interest (PoIs) as they navigate. The system provides feedback through haptic responses, audio cues, and speech, guiding users along the pre-recorded virtual paths. The system was tested in both indoor and outdoor situations, focusing on how well it guides users without physical modifications to the environment. Testing highlighted feedback accuracy, ease of use, and overall user satisfaction.

Zhang and colleagues [3] developed an assistive navigation system (ANSVIP) that enhances indoor navigation for visually impaired users by leveraging ARCore for localization and adaptive path planning for safe and efficient movement. The system uses ARCore, a Google platform for building augmented reality applications, to provide computer vision-based localization. This allows users to navigate without the need for GPS or wireless beacons, making it particularly suitable for indoor use. The system also includes adaptive artificial potential field (AAPF) path planning, which ensures both safe and efficient navigation. It minimizes the chance of collision by generating smooth paths in real time. ANSVIP integrates haptic and audio interfaces. A haptic interface delivers real-time, continuous directional guidance through vibrations, offering a more intuitive experience compared to traditional turn-by-turn audio instructions. While Audio cues are used for macro-level, long-term situational awareness and planning, enhancing the user's understanding of their environment. Testing of the system showed that ANSVIP's continuous guidance is better than conventional navigation systems in terms of obstacle avoidance and ease of use. This approach highlights how integrating advanced computer vision with user-centric feedback can significantly enhance the autonomy of visually impaired individuals in indoor spaces.

In another paper [4], a system designed to assist visually impaired individuals in navigating indoor environments using AR markers and computer vision techniques is presented. The authors proposed an indoor navigation system that helps visually impaired individuals navigate by using AR markers as reference points. The system provides position information to the user through smart devices such as smartphones. The paper introduces a novel method of registering AR markers incrementally in the environment. This allows the system to compute the position of unregistered AR markers relative to those already registered, creating a unified coordinate system. The system uses AR markers generated via the ArUco library, a fiducial marker library that allows for efficient detection and encoding of markers. The algorithm estimates the camera's pose (orientation) and position in relation to the AR markers, solving the 6 Degrees of Freedom (DOF) problem (three dimensions of translation and three dimensions of rotation). Experiments were conducted with the camera recording video to calculate the markers' positions in different frames. These calculated positions were compared with true values to assess the error margins. The accuracy of the system validated through real-world experiments.

3.3. Text Recognition

Studies have been dedicated to creating AR applications that utilize OCR technology to seamlessly convert printed text into audible speech. This innovative approach has opened up possibilities for individuals with visual impairments to effortlessly access and engage with printed materials in their surroundings. Additionally, steps have been taken to enhance the effectiveness and precision of text-to-speech capabilities, further enhancing individuals' accessibility to crucial information [17]. applications hold the potential to transform visual information into non-visual formats too, enabling visually impaired individuals to access and engage with visual content. This can involve converting printed text into speech or Braille, providing audio descriptions to describe visual scenes, and offering access to digital content through non-visual modalities.

In a study a system is designed to convert images containing text into audible speech. This approach utilizes Optical Character Recognition (OCR) to extract text from images and then employs a Text-to-Speech (TTS) engine to vocalize the extracted text. The key goal of the project is to enhance accessibility, particularly for individuals with visual impairments. This module captures a printed document using a camera and processes it to extract text. After text extraction, the system converts the text into speech using machine learning algorithms. It employs the pyttsx3 library for generating speech and aims to improve both the accuracy of text extraction and the naturalness of the speech output. Additionally, the system supports multiple input formats, such as image files, PDFs, and text documents. The project uses tools like Google Lens API and Tesseract for image-to-text conversion, and Google Translate for language translation, enhancing its usability across different languages and user need [17].

3.4. Educational and Vocational Support

AR applications can facilitate access to educational materials, training resources, and workplace accommodations for visually impaired individuals. By providing interactive and accessible learning experiences, AR can support educational attainment, skill development, and employment opportunities for individuals with visual impairments. AR solutions can enhance visual details or provide auditory cues, enabling visually impaired users to access training and educational materials with greater ease, fostering independence and skill development [14].

Hamash and his colleagues explores how Extended Reality (XR) technologies, including Augmented Reality (AR), can transform educational experiences for individuals with visual impairments. The work systematically reviews existing studies on XR applications and their potential to enhance learning for the visually impaired. The review highlights that AR can help improve access to educational resources by providing immersive, multisensory learning environments that include sound, tactile feedback, and spatial audio. The critical point is ensuring that AR applications are fully accessible and provide meaningful sensory input to visually impaired users. The study follows the PRISMA guidelines for systematic reviews, ensuring a comprehensive search across five major databases from 2013 to 2023. It evaluates 71 studies, focusing on trends, limitations, and recommendations for future research [14].

3.5. Social Inclusion and Communication

AR applications can enable visually impaired individuals to engage in social interactions and communication by providing audio-based interfaces, facilitating virtual collaborations, and enhancing access to social media and digital communication platforms. This can contribute to increased social inclusion and connectivity [10].

In a study the development of assistive technologies designed to enhance the social interactions of visually impaired individuals is studied. The study focuses on the implementation of conversational assistive technology using natural language processing (NLP) and machine learning algorithms. These technologies help visually impaired individuals engage in real-time interactions by recognizing spoken language and responding appropriately. Features such as speech recognition, text-to-speech APIs, and vibration alerts are integrated to create an immersive communication experience, which facilitates smoother social engagement and improves overall quality of life. The research employed a heuristic evaluation approach, testing the system's ability to help users perform common social activities like hugging, shaking hands, and talking. The study found that the technology significantly enhances users' social competence, reduces feelings of isolation, and promotes self-confidence. Through real-time interaction, users are able to communicate more naturally in public spaces, work environments, and social gatherings [10].

3.6. Recreational and leisure activities

By utilizing augmented reality (AR), individuals who are visually impaired can enjoy a wide range of recreational and leisure activities. These include engaging audio-based games, immersive storytelling experiences, and culturally relevant content that is easily accessible. Engaging in such activities can greatly benefit an individual's mental well-being and enhance their participation in leisure pursuits, making it a valuable resource for those with visual impairments [11].

Researchers have worked on an AR application that can enhance the connection of visually impaired individuals with nature. The work focuses on using auditory cues delivered via AR to promote nature experiences. The research involved designing an audio-based AR system to provide real-time auditory feedback that enhances the experience of blind and partially sighted users as they navigate open natural spaces. This system augments natural elements by offering immersive auditory experiences, such as sounds of the environment, to improve engagement with nature. The research follows a formative study approach, initially gathering insights from blind and partially sighted individuals about the barriers they face while connecting with nature. Based on these insights, the authors designed the auditory AR system, which was then tested to evaluate its effectiveness in promoting a sense of nature connectedness. The system relies on real-time audio feedback and is designed to improve accessibility for users navigating outdoor spaces [11].

In recent years, there has been a noticeable focus on advancing AR technology for visually impaired individuals. This has resulted in the development of more advanced, precise, and user-friendly solutions to assist those with visual impairments in their daily routines. By harnessing the power of AR, these efforts strive to improve accessibility, self-sufficiency, and involvement for visually impaired users, ultimately promoting inclusivity and independence. AR applications can support visually impaired individuals in performing daily tasks independently, such as identifying objects, reading instructions, managing personal finances, and accessing public services. By providing real-time support and information, AR can empower individuals to navigate various aspects of daily living with greater autonomy. Figure 1. Shows the enhancement AR can bring to visually impaired people.

4. AR usability challenges for visually impaired

While the potential of AR for visually impaired individuals is promising, there are challenges and limitations that researchers have identified. AR applications often rely on object recognition and tracking to overlay virtual content onto real-world objects. However, visually impaired users may face challenges in accurately recognizing and tracking objects due to limited or no visual cues [18]. This can affect the accuracy and reliability of AR applications for visually impaired individuals. Moreover, tool limitations may hinder the accuracy

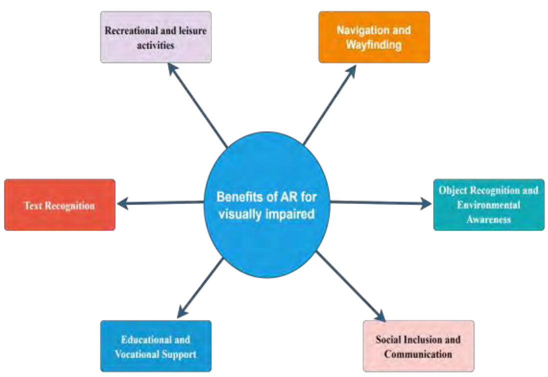

Figure 1. benefits of AR for visually impaired people

and reliability of object recognition which is essential for a blind user who utilizes an AR application. A camera with a lower resolution that utilizes compressed images, resulting in reduced detection accuracy and limited tool capabilities diminishes object recognition reliability [19].

It can be quite difficult for visually impaired individuals to master the use of AR applications, particularly if these apps lack clear and accessible instructions for interaction. As a result, this poses a challenge to their adoption and usability, as these users may need more time and assistance to become acquainted with the technology [20].

Further, AR applications heavily rely on spatial awareness and orientation as well as visual content, such as images, videos, and 3D models, which can be inaccessible to visually impaired users. They may face difficulties in perceiving and understanding the spatial relationships between virtual and real-world objects [21, 22].

The design of AR user interfaces can also, pose challenges for visually impaired users. Complex or cluttered interfaces, small text, or unclear navigation can make it difficult for them to interact with the application effectively. Lack of proper contrast, color coding, or tactile feedback can also hinder their ability to navigate and understand the interface [23].

Visually impaired users may require training and familiarization with AR applications to understand their functionalities and effectively use them. Many AR tools require tailored orientation and mobility (O&M) training, which is crucial for visually impaired individuals to navigate digital and physical spaces confidently. For instance, a 2022 study on audio-augmented reality-based O&M training for visually impaired children found that accessible, engaging training methods, such as gamification and audio cues, significantly improved user experience [5]. The lack of accessible training resources or support can hinder the adoption of AR for visually impaired individuals. Providing accessible, user-friendly training materials is vital for ensuring these users can fully engage with AR applications.

They may also face social acceptance challenges when using AR applications in public spaces. The use of wearable devices or gestures for interaction can draw attention and potentially lead to stigmatization or discomfort. Addressing these challenges requires a user-centered design approach that considers the specific needs, preferences, and abilities of visually impaired users [24].

A multitude of AR applications heavily depend on visual indicators and a keen sense of space, making them considerably more complex for individuals with visual impairments [25]. Some AR applications lack the necessary accessibility features for individuals with visual impairments. This means that users who rely on screen readers, voice commands, and other assistive technologies may face difficulties interacting with the application [26]. Without suitable auditory or tactile cues, maneuvering through AR environments and grasping the connections between virtual and physical components proves to be a daunting task.

AR applications can overwhelm people with visual impairments due to the excessive amount of visual information they present [27]. If this information is not strategically designed, it may not be effectively communicated through non-visual means, resulting in the loss of necessary contextual information.

The effectiveness of AR applications for visually impaired individuals may be influenced by the physical surroundings in which they are utilized [20]. Elements such as lighting, noise levels, and obstacles present in the environment have the potential to affect the usability of AR apps for those with visual impairments. Figure 2. demonstrates AR challenges for visually impaired individuals.

Creating effective solutions for usability challenges in AR applications involves a mindful approach to design and development. Researchers have delved into the creation of user interfaces and interaction methods that cater to the unique needs of individuals with visual impairments. These investigations have focused on developing intuitive, accessible, and personalized designs. This has involved exploring various non-visual interaction techniques, implementing haptic feedback, and incorporating gesture-based controls to optimize the usability of AR applications.

5. Usability guidelines of AR applications for users with visual impairments

Research on the use of augmented reality (AR) for visually impaired individuals has shown promising results and has garnered attention from researchers in various fields. Researchers recognize

Figure 2. challenges of AR for visually impaired people

the potential of AR to enhance the lives of visually impaired individuals by assisting in navigation[1-5], object recognition [6-8], education [14], social interaction[10], and more.

It is important to note that while AR holds great potential for visually impaired individuals, its successful implementation requires careful consideration of usability guidelines, accessibility features, and user-centered design principles [28]. This ensures that AR applications are intuitive, inclusive, and effectively address the specific needs and challenges faced by visually impaired users and helps design interfaces that are easy to navigate, provide clear and concise instructions, and offer appropriate feedback. This enhances the overall user experience and increases user satisfaction. Developers should anticipate and address common pitfalls, such as unclear instructions, confusing navigation, or inaccessible content. Following usability guidelines helps in identifying and preventing potential errors or usability issues in AR applications. This reduces frustration and improves the overall usability of the application [29].

Usability guidelines also play a role in addressing ethical considerations related to AR applications [30]. By ensuring that applications are designed with user-centered principles and prioritize user safety and privacy, these guidelines help in building trust and maintaining ethical standards in the development and deployment of AR technologies [31].

However, there is a lack of research that comprehensively addresses all aspects of improving the usability of augmented reality applications for visually impaired individuals. It highlights the position of this research which reports on usability approaches that are essential in designing and developing AR applications for users with visual impairments. Following we discuss several usability guidelines which are emphasized in the literature.

Developers are recommended to design applications that are compatible with assistive technologies [32], such as screen readers or braille displays, and provide text-to-speech capabilities. This allows visually impaired users to effectively interact with the AR content and access the information provided.

Usability guidelines promote consistency in the design and functionality of AR applications. Consistency ensures that visually impaired users can easily understand and predict how the application will behave. This reduces cognitive load and allows users to focus on the task at hand, rather than spending time and effort in figuring out how to interact with the application. Consistency in user interfaces is crucial for easy task performance, as it involves consistent naming, labeling, and command structures. Lack of consistency poses challenges for blind users to remember actions, increases the learning curve, and hinders the discovery and execution of common activities [24].

Integrating collaborative and social elements into AR apps, can open up possibilities for the visually impaired to engage with those who can see, ultimately improving accessibility and social integration. Innovative features such as audio-based communication, shared virtual environments, and collaborative navigation greatly enhance the usability and overall user experience of such applications [10].

Designing a clear and accessible user interface with high contrast, large and legible text, and well-organized menus is also essential [32]. The interface elements should be easily distinguishable and labeled clearly for screen reader compatibility [33, 34]. Virtual objects should also have a larger hit area to facilitate easier selection and manipulation. Using visual cues, such as color coding or symbols also can be interpreted by users with residual vision or low vision and enhance their interactions.

Researchers emphasize the importance of user-centered design and accessibility in developing AR applications. This includes considering the specific needs, preferences, and abilities of users, as well as incorporating accessibility features such as alternative text, audio descriptions, and haptic feedback [2, 3, 18, 32, 35]. For instance, when a visually impaired user encounters a virtual object, the application can provide an audio description like "A red chair with a cushion on the seat." A crucial aspect of optimizing the user experience and functionality of the application is delivering precise and applicable audio and tactile cues that are aligned with the user's location and orientation within the augmented reality (AR) environment [36]. As shown in Table I, the most commonly employed technique in papers to enable visually impaired users to interact with the AR application is through audio input and feedback.

Designing intuitive and tactile interaction techniques that allow visually impaired users to navigate, select, and manipulate virtual objects in the AR environment, can cater AR applications to a wider range of users. Incorporating alternative sensory cues such as gestures, voice commands, and physical controllers that provide tactile feedback, ensures that AR applications convey information and enhance the user experience [24, 37].

Implementing collision detection to prevent accidental interactions and providing audio or haptic feedback when virtual objects interact with real-world, enhances spatial awareness and orientation of visually impaired users. Using spatial audio cues to indicate the location and proximity of virtual objects

Table 1. Usability approaches

Ref.	***Type of application***	***Usability approach***
[1]	Indoor navigation	Audio
[2]	Localization and navigation both indoors and outdoors	Haptic, Speech, Audio
[3]	Indoor navigation	Haptic, Audio
[4]	Indoor navigation	Audio
[5]	orientation training	Audio
[6]	Object detection, obstacle notification, and navigation	Audio
[7]	The positioning and categorization details of various obstacles	Audio
[8]	Object detection	Audio
[9]	determining the location of the medicine and the quantity of pills	Audio
[10]	Social interaction	speech recognition, text-to-speech
[11]	Entertainment	Audio
[12]	Text recognition	Audio
[18]	Furniture placement, object recognition, education	Freezing, Audio, haptic
[32]	Outdoor navigation	Audio
[33]	Document reading	Audio, tactile
[35]	Navigation	speech recognition
[37]	Navigation	Audio, tactile
[39]	Education	Audio, tactile
[41]	Location announcement	Tactile
[42]	Navigation	Audio

or important points of interest and utilizing audio feedback to convey changes in the AR environment, such as object movement or environmental conditions help them understand the layout of the AR environment and navigate through it effectively [24]. Providing contextual information about the AR environment, such as location-based information, directions, and points of interest assists visually impaired users in understanding their surroundings and making informed decisions. For example, when a visually impaired enters a new area in the AR environment, the application can provide audio instructions like "Turn left and walk straight for 10 meters to reach the next point of interest". Coughlan and Miele [38] have introduced an application named overTHERE which is capable of rotating and maneuvering the device to align it with a desired location of interest to access supplementary details.

Adding the "freeze" feature to AR application, also allows users to capture a stable view of the AR content and interact with virtual objects without worrying about device movement [18]. This is particularly beneficial for visually impaired users, as it eliminates the need to constantly align the device with virtual objects. Non-visual camera aiming is challenging, especially when users need to maintain a stable position while interacting with the device.

It is also recommended to allow individuals to customize the interface based on user preferences and needs by providing options for adjusting font size, contrast, color schemes, audio settings, and the ability to adjust the level of detail and complexity of AR information based on user preferences to accommodate individuals with visual impairments. This ensures that visually impaired individuals can fully participate and benefit from the AR experience [37].

Continuous enhancement of AR applications for visually impaired users requires user testing and feedback. Conducting user testing with visually impaired individuals throughout the design and development process to gather feedback and insights and incorporating their input, improves the usability and accessibility of the AR application. Moreover, engaging in collaborations with accessibility organizations and advocacy groups that prioritize accessibility and visual impairment is crucial for gaining valuable insights and receiving feedback. This collaboration ensures that AR technology effectively caters to the needs of the user community [39].

Finally, offering comprehensive training and support resources, including tutorials, guides, and access to technical assistance, to help visually impaired users learn how to use AR applications effectively can enhance their experience with them [5, 40].

In summary, usability guidelines for AR applications are essential for ensuring accessibility, enhancing the user experience, promoting consistency, preventing errors, fostering inclusivity, and addressing ethical considerations. By following these guidelines, developers can create AR applications that are usable, effective, and beneficial for visually impaired individuals while prioritizing user privacy, and security, with a deep understanding of the potential impact on the user's daily life.

The studies reviewed in this research highlight the importance of considering usability guidelines in the design and development of AR applications, both in general and for visually impaired users. They provide valuable insights and recommendations for creating accessible, user-friendly, and effective AR experiences. However, these guidelines should be used as a starting point and should be adapted and refined based on the specific needs and preferences of visually impaired users. User-centered design and continuous feedback from visually impaired individuals are crucial for creating truly accessible and usable AR applications. It is important to note that the field of AR usability guidelines is continuously evolving, and further research is needed to address emerging technologies and user needs. Guidelines for developing AR applications for visually impaired people is presented in Figure 3.

It should be noted that while papers investigated in this research mostly report on accessibility features they applied (as summarized in Table 1), they lack clear and detailed descriptions of other usability guidelines highlighted in this research. There is no report on how they followed consistency and customization in their design, how well organized they designed menus, or how they engaged the visually impaired in their design and development process. We hope that highlighting visually impaired concerns in this research helps develop AR applications that are further usable for this community.

6. Introducing visually impaired AR applications concerning suggested usability guideline

In the rest of this paper, we introduce a couple of existing AR applications designed for visually impaired users and analyze how these applications adhere to the usability guidelines.

Seeing AI: Developed by Microsoft, is a popular AR application that uses computer vision and natural language processing to assist visually impaired individuals. It can recognize and describe objects, read text, identify people, and provide audio guidance for navigating the environment. The app uses the smartphone's camera to interpret visual information, converting it into audible feedback to help users better understand their surroundings. It is available for iOS devices and offers several key features. The app instantly reads out short pieces of text, such as signs or labels, as soon as they are captured by the camera. It Recognizes and reads full pages of printed text, assisting users in reading longer materials like books, letters, and forms. Seeing AI scans barcodes to identify products. Once a barcode is detected, the app provides information about the product. Recognizing and describing people in the camera's view, providing information about their facial expressions, age, gender, and more is another capability of this app. It further provides general descriptions of scenes by interpreting objects, activities, and environmental details within the camera’s field of view. Currency Identification, light intensity detection, color recognition are other features of Seeing AI app [43]. This application adheres to guidelines related to audio feedback, object recognition, and customization and provides clear and concise audio descriptions, object recognition, and navigation assistance.

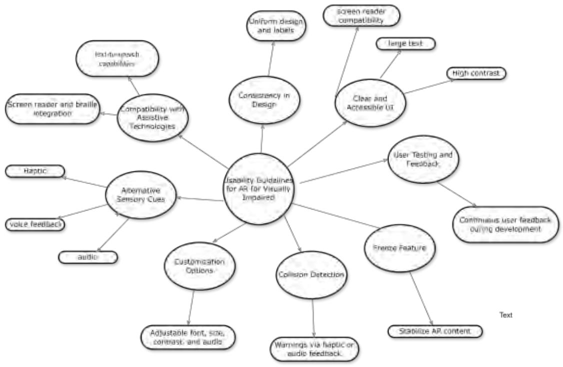

Figure 3. usability guidelines for AR applications for visually impaired people

Aipoly Vision is another AR app using object recognition technology to help visually impaired users identify and understand their surroundings. It identifies objects, text, and colors in surroundings through the camera of a smartphone. Aipoly Vision uses computer vision and deep learning algorithms to analyze the images captured by the smartphone's camera. The core of Aipoly Vision relies on convolutional neural networks (CNNs), which are commonly used in real-time image recognition tasks. Aipoly Vision is also capable of identifying colors. It can distinguish between over 1,000 colors. It also includes an Optical Character Recognition (OCR) feature, allowing it to recognize and read out printed text (e.g., signs, labels, books). After processing the visual information, the app provides audio feedback through speech. The app can speak in multiple languages, making it accessible to a global audience. Aipoly Vision can operate offline once its machine learning models and databases are downloaded, which is important for accessibility in areas with no internet connection. Users can adjust settings to focus on specific tasks like color identification, object recognition, or text reading, optimizing the experience based on their needs. The app is designed to be highly user-friendly, with an interface that can be easily navigated by individuals with visual impairments. Voice commands and gesture-based controls are part of the app to enhance accessibility [44]. Aipoly Vision aligns with guidelines related to object recognition and audio feedback.

NavCog is an augmented reality (AR) navigation app developed by IBM Research in collaboration with Carnegie Mellon University [45]. It is specifically designed to assist visually impaired individuals in navigating complex indoor and outdoor environments. NavCog uses Bluetooth beacons and smartphone sensors to provide precise turn-by-turn navigation. It communicates information to users via auditory cues, allowing them to move independently in spaces like university campuses or other public buildings. The app is part of a broader initiative aimed at creating open-source tools for developers to build AR applications that enhance accessibility for the blind. By utilizing cognitive technologies and environmental sensors, NavCog provides real-time localization and navigation assistance, which can help improve independence and mobility for visually impaired user. This app aligns with guidelines related to navigation and interaction.

ARtSENSE: It is an augmented reality (AR) initiative aimed at enhancing the museum experience, especially for individuals with visual impairments. The project integrates adaptive AR technology using real-time sensor data such as eye-tracking, physiological sensing, and spatial audio to create personalized and responsive interactions with museum exhibits. ARtSENSE allows artworks to "respond" to the user’s attention, engagement, and emotional state, enhancing accessibility and creating a more immersive experience. The system also includes gesture-based interaction and audio augmentations, which make the physical objects feel dynamic and interactive, providing a richer and more inclusive museum experience. The ARtSENSE project collaborated with cultural institutions like the Museo Nacional de Artes Decorativas in Madrid and the Musée des arts et métiers in Paris to create adaptive cultural experiences for a diverse audience, including those with disabilities [46]. ARtSENSE adheres to guidelines related to visual representation and customization.

AR for Accessibility: This project by the University of Hawaii explores the use of AR to improve accessibility for visually impaired users [36]. It aims to utilize AR technologies to provide better navigation, improved learning experiences, and overall enhanced interactions for people with visual impairments. The research emphasizes user-centered design principles, creating tools and interfaces that cater to the needs of the visually impaired, integrating audio and tactile feedback to augment the AR experience beyond just visual elements. It aligns with guidelines related to audio feedback, object recognition, and navigation assistance.

These examples demonstrate how AR technology can be utilized to create applications that assist visually impaired individuals in various aspects of their daily lives, including object recognition, navigation, and access to information. They enhance accessibility by providing alternative means of perceiving and interacting with the environment to provide information and assistance that would otherwise be inaccessible to visually impaired individuals. By leveraging AR technology, these applications empower visually impaired users to perform tasks independently that would typically require assistance. This increased independence enhances their confidence and overall quality of life. AR applications designed for visually impaired users facilitate greater engagement with the world around them. By providing audio descriptions, tactile models, and haptic feedback, these applications enable visually impaired individuals to explore and understand their environment in a more immersive and interactive manner. This leads to a richer and more engaging experience. These applications bridge the information gap by providing real-time access to information that would otherwise be visually presented. For instance, applications like ARtSENSE enable visually impaired users to access audio descriptions of artworks in museums, allowing them to appreciate and understand the art in a meaningful way. This access to information promotes inclusion and equal participation.

7. Discussion and Conclusion

As the field of AR continues to grow and evolve, there are numerous opportunities for further investigation and progress in creating accessible, user-friendly, and effective applications for visually impaired individuals. following we discuss some of the potential areas for future research and development.

Further investigation is necessary to enhance the accuracy, speed, and robustness of object recognition in augmented reality (AR) programs for individuals with visual impairments. This entails creating more advanced computer vision algorithms, utilizing deep learning methods, and expanding the range of objects and environmental contexts that can be accurately identified and described.

Additionally, the advancement of indoor navigation and localization systems can effectively guide visually impaired individuals within complex indoor environments, such as spacious buildings, shopping malls, and public facilities. This involves investigating the utilization of technologies like Bluetooth beacons, WiFi-based positioning, and other methods to offer accurate support for indoor navigation.

Ongoing studies on AR applications that enhance social interaction and communication for individuals with visual impairments, incorporating features like face recognition, social cues, and support for collaborative experiences with sighted peers, can further enhance the usability of these applications.

Optimizing the user experience, minimizing technical barriers, and ensuring interoperability with existing accessibility tools and platforms are other areas for further research.

By addressing these areas for further research and development, the field of AR applications for visually impaired individuals can continue to evolve, providing more comprehensive and effective solutions to enhance accessibility, independence, and engagement for users with visual impairments.

Considering usability guidelines is of utmost importance to ensure the accessibility and effectiveness of augmented reality (AR) applications for the visually impaired. These guidelines provide a framework for designing and developing applications that cater to the unique needs and challenges faced by visually impaired individuals. By adhering to these guidelines, developers can create applications that enhance accessibility, promote independence, and improve the overall user experience.

Usability guidelines emphasize the importance of accessibility, user-centric design, multimodal interaction, customization, compatibility with assistive technologies, and continuous improvement. By incorporating these principles into the design and development process, AR applications can provide non-visual cues, such as audio feedback, haptic feedback, and tactile interfaces, to enable visually impaired users to perceive and interact with their environment effectively.

Considering usability guidelines also ensures that AR applications are customizable, allowing users to adjust settings according to their preferences and needs. This flexibility enhances usability and accommodates the diverse abilities and requirements of visually impaired individuals.

Furthermore, usability guidelines emphasize the significance of continuous improvement through user testing and feedback incorporation. By actively involving visually impaired users throughout the design and development process, developers can address usability issues, refine the application, and ensure that it evolves to meet the changing needs and expectations of users.

By prioritizing usability guidelines, we can create AR applications that empower visually impaired individuals, enhance their independence, and provide them with equal access to information and opportunities. These applications have the potential to transform the lives of visually impaired users, enabling them to navigate their surroundings, understand their environment, and engage with the world in a more inclusive and meaningful way.

By considering usability guidelines, we can ensure that AR applications for the visually impaired are not only accessible but also effective, providing a transformative and empowering experience. Designers, developers, and researchers must continue to prioritize usability guidelines and conduct further research to advance the field of AR accessibility, ultimately improving the lives of visually impaired users.

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Authors' contributions

NZ: Study design, acquisition of data, interpretation of the results, drafting the manuscript;

ZA: Study design, revision of the manuscript.

Conflict of interest

The authors declare that no conflicts of interest exist.

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