Designing a Mixed Reality Model for Hearing Impaired Users Based on Assistive Technology, Empathic and Visual Interaction Design Principles through Comparative Analysis

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***Abstract* – Mixed Reality (MR) is an innovative technology with the potential to support diverse user groups including people with disabilities (PWDs) such as people with hearing impairments. Despite advancements in MR, limited research has explored integrating assistive technology (AT), empathic design (ED), and visual interaction (VI) principles in the development of MR to address the unique challenges faced by the hearing-impaired (HI) people.**

Therefore, this study aims to fill this gap by proposing a MR model tailored to meet the specific requirements of HI users, integrating AT, ED, and VI design principles. Prior to achieving the main aims, this study needs to explore the main components, elements and design principles of existing MR models for HI users. Hence, the main objectives of this paper are (i) To identify the components, elements and design principles of the MR model for HI and (ii) To design the initial MR model through comparative analysis method. By integrating AT, ED, and VI principles, this research contributes valuable insights for advancing inclusive MR applications to support social equality for the HI community.

***Keywords* – Mixed reality, assistive technology, empathic design, visual interaction design, hearing impairment.**

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1. Introduction

The Forth Industrial Revolution (IR4.0) has amplified the significance of immersive technologies such as Mixed Reality (MR) technology. There are countless MR applications that have been developed and currently available in the market with the goal of meeting the needs of various intended user groups including people with disabilities (PWDs). These immersive applications provide creative ways to improve regular activities and general quality of life, which is especially helpful for those with many kinds of disabilities or impairments [21].

But recent developments of MR technology have mostly concentrated on improving the motor skills for people with physical disabilities or motor problems, thus ignoring the needs of MR for the hearing-impaired (HI) people [1].

Many studies also suggest that MR technology can greatly improve sensory experiences and increase user engagement for HI people. For instance, studies have shown that by providing visual and contextual clues that are specifically designed to meet the communication needs of HI people, MR can improve learning experiences and promote interactions [37]. Additionally, extant literature emphasizes the need for additional advancements in this field to fully realize the advantages of MR for the HI. Therefore, this study aims to propose a MR model based on assistive technology (AT), empathic design (ED), and visual interaction design (VI) for HI people.

1.1. Mixed Reality (MR)

Mixed Reality (MR) was ranked among the top ten Information and Communication Technology (ICT) advancements in 2020, with extensive research exploring its applications across various domains [29], [30]. MR is an advanced technology that seamlessly integrates the physical and digital worlds, creating interactive environments where real and virtual elements coexist and interact in real time. Often referred to as hybrid reality, MR allows users to engage with objects that exist simultaneously in both physical and virtual spaces.

Furthermore, [6] draws a distinction between AR and augmented virtuality (AV) within the MR spectrum, as seen in Figure 1, stating that while AR superimposes digital content in the real world, AV incorporates real things into a virtual setting. In the era of IR4.0, the changing digital landscape highlighted MR's revolutionary potential to change how users interact with and perceive the outside world.

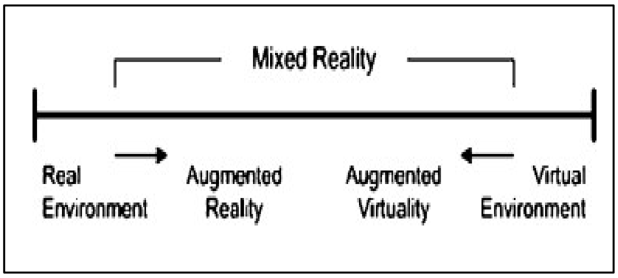

Figure 1. Reality continuum of mixed reality

In addition, the need for Wearable Assistive Technologies (WATs), which are essential in resolving the functional difficulties encountered by people with impairments, has significantly increased, according to [5].

WATs improve user engagement in MR environments as a subset of assistive technology. MR was chosen for this study to create and design a model specifically for HI people because of these benefits. The goal of MR technology adoption is to utilize its potential to develop a novel and engaging tool that can greatly improve communication for HI people. Details on the AT were discussed in the following subsections.

1.2. Assistive Technology (AT) Design Principles

There are many existing assistive technology (AT) products that are designed with a focus on inclusivity to minimize development costs [12]. However, they often fail to address the specific needs of HI individuals regarding visual interaction, leading to critical accessibility issues being overlooked [28]. Besides, an improperly designed AT device has the potential to negatively impact on the user's physical well-being, possibly leading to strain, discomfort, or even long-term health issues. According to [35], even seemingly simple devices, if not thoughtfully designed, can result in adverse physical consequences for the user. For instance, a poorly designed walking cane might cause improper posture, leading to back pain or joint problems over time.

AT design principles aim to enhance accessibility, independence, and capabilities for individuals with disabilities. These principles prioritize inclusivity, effectiveness, and user-centricity. Table 1 outlines six AT design principles by [4]. Designing for hearing impairment presents unique challenges, requiring solutions that address specific accessibility and empathic needs. Research highlights a gap in addressing the diverse challenges faced by individuals with varying degrees of HI, which differ significantly from other impairments [3].

Integrating empathic design (ED) is essential, as it helps developers understand users' perspectives, perceptions, and emotional responses to products or services [19], [18]. The following sections discuss in detail the ED principles.

Table 1. Basic principles of assistive technology (AT)

No	Design Principles	Description
1	Accessibility	Technology should be used by people with various disabilities. It should be designed to be easily accessible to everyone, regardless of disability.
2	Adaptability	Technology should be flexible and able to adapt to the users' needs, allowing for customization and modification.
3	Affordability	Assistive technology should be affordable, ensuring that cost is not a barrier to access for users who need it.
4	Availability	Technology should be widely available to those who need it, ensuring that it is easy to obtain or access.
5	Acceptability	Technology should be accepted by users, caregivers, and society. This involves considering cultural and social factors.
6	Quality	Technology must be reliable, durable, and of high quality to ensure it performs effectively and lasts overtime.

1.3. Empathic Design Principles (ED)

Empathic Design Principles (ED) encompasses methods and techniques that enable design teams to uncover users' hidden needs, expectations, aspirations, and preferences [33]. These approaches focus on understanding people's emotions and life experiences to guide and inspire the design process [32], [31]. By immersing themselves in users' daily lives and engaging directly with potential users and stakeholders, designers gain unique perspectives informed by personal experiences and emotions. This perspective complements insights derived from other research methods, such as market analysis [27].

ED principles focus on understanding and addressing users' emotional, experiential, and functional needs, enabling meaningful and accessible solutions. These principles as outlined by [20] were shown in Table 2. However, current immersive technologies often prioritize solutions for visual impairments, which differ greatly from the needs of HI individuals. While visually impaired users rely on auditory cues, HI users depend on visual cues for interaction [22]. As emphasized by [2], the need for alternative visual signals to effectively convey information and feedback for HI users, contrasting with [28] focus on auditory cues for visually impaired users.

This study advocates integrating visual interaction (VI) design principles to improve usability, aesthetics, and user satisfaction through optimized visual elements in digital interfaces. The details on the visual interaction design principles were discussed in the following subsections.

Table 2. Basic principles of empathic design (ED)

No	Design Principles	Description
1	Clarity of Instruction	Provide clear, concise, and intuitive guidance to users to ensure they understand how to interact with the design effectively.
2	Ease of Use	Design interfaces and interactions that are simple, intuitive, and require minimal effort to navigate or operate.
3	Engagement	Foster user interest and motivation by creating interactive, appealing, and emotionally resonant experiences.
4	Interactivity	Enable active participation and responsiveness in the design, allowing users to feel involved and in control.
5	Learning Progression	Support step-by-step mastery or development of skills through adaptive and structured learning pathways.
6	Rewards	Motivate users with feedback, achievements, or gamified incentives that reinforce positive behaviors and continued use.
7	Support Resources	Provide accessible tools, guides, or assistance to empower users and ensure inclusivity.
8	Task Efficiency	Optimize processes and reduce complexity to save users' time and effort, enhancing overall productivity.
9	Visual Design	Use aesthetic, accessible, and functional visual elements to improve user experience and communication clarity.

1.4. Visual Interaction (VI) Design Principles

Visual Interaction (VI) design principles are a fundamental component of user interaction and experience design. It focuses on the aesthetics and usability of digital interfaces, blending interaction design principles, user interface design, and visual design to create an engaging and effective user experience. Furthermore, visual interaction design plays a critical role in digital products, services, and experiences by utilizing visual cues, auditory cues, and feedback [26].

The goal is to provide an immersive and responsive experience that is seamless and intuitive, which is especially important for PWDs particularly those with hearing impairments, to effectively carry out their daily tasks [16].

By integrating these design principles, designers can ensure that their digital interfaces are accessible and usable for a wider audience, including individuals with hearing impairments [13]. Table 3 depicts the list of VI basic design principles by [23].

Table 3. Basic principles of visual interaction (VI)

No	Design Principles	Description
1	Consistency	Ensuring that design elements and interactions are uniform across the interface, creating familiarity and reducing cognitive effort for the user.
2	Feedback	Providing immediate, clear, and meaningful responses to user actions, helping users understand the result of their interactions.
3	Visual Hierarchy	Organizing content and interface elements in a way that guides users' attention to the most important information first, using size, color, and placement
4	Affordance	Designing interface elements in a way that suggests their functionality, e.g., buttons that look clickable or sliders that suggest movement.
5	Aesthetic and Simplicity	Prioritizing a clean and visually appealing design, minimizing unnecessary elements to create an intuitive and enjoyable user experience.
6	User Control	Allowing users to feel in control of the interface and enabling them to make decisions and undo actions easily.
7	Accessibility	Designing for inclusiveness, ensuring the system is usable by individuals with diverse needs and abilities (e.g., vision impairment, motor difficulties).
8	Flexibility and Efficiency of Use	Allowing customization and enabling more experienced users to interact with the system more efficiently, e.g., through shortcuts or personalized settings.
9	Error Prevention and Recovery	Designing the system to minimize errors and offering clear paths for users to recover from mistakes when they occur, such as clear undo options.
10	Learnability	Making the interface easy to learn by providing clear navigation, intuitive icons, and familiar patterns that reduce the time needed to master the system.
11	Context Awareness	Designing the system to recognize and adapt to the user's context (e.g., location, device, task), providing relevant information and actions.
12	Trustworthiness	Creating a design that fosters user trust through clear communication and consistency in design elements.
13	Cognitive Load Reduction	Minimizing the mental effort required to interact with the system by simplifying tasks, providing helpful cues, and reducing distractions.
14	Responsiveness	Ensuring the interface responds promptly and accurately to user inputs, maintain a fluid and smooth interaction experiences.
15	Task Relevance	Prioritizing content and actions that are directly related to the user's current goals or tasks, minimizing irrelevant information or options.
16	Personalization	Allowing users to adjust or personalize the interface to meet their preferences or needs, increasing comfort and enhancing user experience.
17	Discoverability	Ensure users can easily find and understand all available actions and options.
18	Engagement	Incorporates subtle animations, transitions, or effects to enhance the user experience and evoke positive emotions.

To summarize, addressing visual interaction needs for HI people in the development of MR requires adaptable and flexible design solutions to accommodate different levels of hearing impairment. Thus, this study proposes integrating MR, AT, ED and VI design principles to cater to the specific needs of HI users.

This is to enhance their functionality and interaction experiences across various contexts. In conjunction with that, this paper aims to identify the components, elements and design principles for the proposed MR model for HI through comparative analysis method. The following sections discuss in detail the process of identifying the components, elements and design principles.

2. Methodology

This section provides a detailed explanation of the method used to identify the proposed MR model for individuals with hearing impairments. Figure 2 illustrates the activities involved in the research, which are divided into two phases: (i) Phase 1: Literature Review and (ii) Phase 2: Comparative Analysis.

Table 4 provides a comprehensive list of the identified MR models for HI users. These findings were subsequently compared to determine the common components, elements, and design principles, which are discussed in detail in the following section.

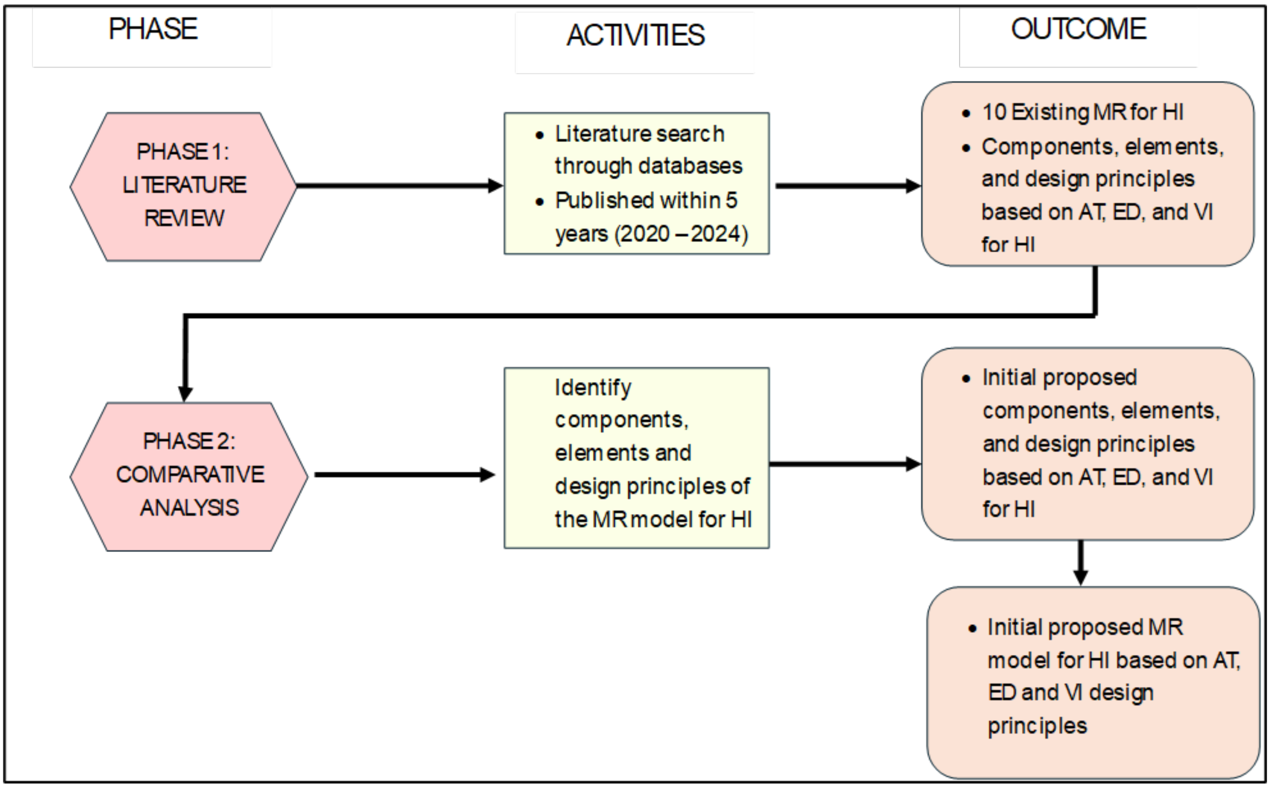

Figure 2. Research activities

2.1. Phase 1 - Literature Review

During this phase, all articles or academic papers related to the existing MR for HI were elicited from various listed databases such as IEEE, Scopus, Science Direct, and Google Scholar. By adopting this approach, the study ensures a balanced yet manageable scope for evaluation. This analysis will systematically assess the strengths, limitations, and unique characteristics of each model, offering critical insights to develop an innovative MR framework.

In addition, the literature was elicited in a range from 2020 to 2024 as suggested by [8]. Also, [8] highlights that technological progress often evolves rapidly and can include disruptive innovations that reshape industries within a short timeframe. Therefore, by analyzing developments over the past five years, this review captures significant advancements, ensures the research is current, and maintains a scope that is both thorough and manageable.

Then, comparative analysis was conducted to identify the gaps to be filled in by this study and the components, elements, and design principles of the proposed MR model for HI. The results were discussed in the following section.

2.2. Phase 2 - Comparative Analysis

A comparative analysis is a systematic method used to evaluate and contrast different entities to understand their similarities and differences [9]. In this study, the comparative analysis aims to identify the components, elements, and design principles that will serve as the foundation for the proposed MR model. By analyzing and comparing these criteria across existing MR models, the study ensures the development of a robust model.

As suggested by [9], examining a sample of ten models is typically sufficient to derive meaningful insights in a comparative analysis process.

Guided by this, a selection of MR models will be reviewed to evaluate their components, elements, and design principles based on AT, ED and VI. The insights gained from this process will inform the proposed MR model by identifying the most relevant and effective elements to include.

The frequency of occurrence of the identified components, elements, and design principles was also calculated and ranked in descending order. Additionally, the percentage frequency of occurrence was determined using a standard formula for quantitative analysis, as recommended by [9]. The use of frequency and percentage calculation to determine which components, elements and design principles appear most often and to compare the relative importance or prevalence of each component within the total dataset. The results were then listed in descending order to show the most common to the least common components.

The formula was described as follows:

a) Frequency of Occurrence: This is to simply the count of how often a specific component, element, or design principle appears in the analyzed models.

F = Count of Occurrence of the Design Elements, Components and Design Principles

b) Percentage Frequency of Occurrence: This formula calculates the proportion of each component's frequency relative to the total frequency of all components.

Percentage Frequency = (Frequency of Component / Total Frequency of All Components) x 100

Then, the results were categorized under three categories (high, medium and low) according to the GRADE approach as suggested by [14].

Additionally, each category was colored with different colors to show the differences which high (red), moderate (yellow) and low (green). This is to sort out the importance of the components, elements, and design principles in designing the MR model for HI.

The outcomes of this comparative analysis will play a critical role in shaping the initial structure of the proposed MR model, providing a comprehensive understanding of its foundational aspects. These findings will be elaborated upon in subsequent sections to underscore their significance and relevance to the study.

3. Results

This section provides a detailed discussion of the findings from the literature review and comparative analysis. The outcomes were analyzed and presented in the following subsections to offer a comprehensive understanding of the key insights. The discussion is structured as follows:

3.1. Existing Mixed Reality Model for Hearing Impaired (2020 – 2024)

Through the literature review process, 10 articles on existing MR models for HI individuals, published between 2020 and 2024, were analyzed. The review focused on identifying key components, elements, and design principles related to assistive technology (AT), empathic design (ED), and visual interaction (VI).

Table 4 provides a comprehensive list of the identified MR models for HI users. These findings were subsequently compared to determine the common components, elements, and design principles, which are discussed in detail in the following section.

Table 4. Existing mixed reality model for hearing impaired (2020 – 2024)

Model No	**Paper**	**Design Components**	**Design Elements**	**Design Principles**		
				Assistive Technology	**Empathic Design**	**Visual Interaction**
1	[34]	Customizable Avatar Appearance	Avatars customization option (tailored to reflect individual needs, such as size, color, and hearing-related features)	Adaptability	Engagement and Visual Design	Personalization and User Control
		Gesture Recognition (Lip reading and facial expression)	Gesture tracking systems that detect lip movements and facial expressions	Accessibility	Ease of Use and Interactivity	Affordance and Feedback
		Sign language Integration	Sign language animation libraries	Acceptability	Support Resources	Accessibility and Intuitiveness
		Visual Cues	Visual notifications or alerts for real-time interaction and provide sound cues for conversational turns	Quality	Clarity of Instruction and Visual Design	Consistency, Feedback and Cognitive Load Reduction, Visual Hierarchy
2	[25]	3D Sign Language Avatar	3D Avatar Rendering Engine	Adaptability	Visual Design	Accessibility
		AR Integration	AR Glasses	Availability	Ease of Use	Context Awareness
		2D-to-3D Conversion	2D Video Processing Module for Gesture Extraction	Quality	Task Efficiency	Scalability
		Real-time Gesture Display	Avatar Animation and Gesture Translation System	Accessibility	Interactivity	Feedback
		Feedback Loop for Gesture Accuracy	Feedback System for Gesture Refinement	Acceptability	Learning Progression	Error Prevention and Recovery
3	[38]	Real-Time Speech-to-Text Captioning	Speech Recognition and Captioning Module	Accessibility	Clarity of Instruction	Accessibility and Responsiveness
		Visual Cues for Speaker Identification	Speaker Identification and Highlighting System	Adaptability	Visual Design and Clarity of Instruction	Feedback and Consistency
		Gesture-Based Interaction	Gesture Recognition Interface	Quality	Ease of Use and Interactivity	Affordance and User Control
		Customizable Display Options	Customizable User Interface Settings	Acceptability	Visual Design	Personalization and Cognitive Load Reduction
4	[36]	Holographic Sign Language Avatar	3D Avatar Animation for Sign Language	Accessibility	Engagement	Accessibility and Intuitiveness
		Virtual Environment	MR Headset	Availability	Interactivity	Context awareness and Scalability
		Gesture Recognition	Interactive Controls for Gesture Commands	Quality	Ease of Use and Interactivity	Affordance and User Control
		Real Time Sign Translation	Compatibility with Classroom Technologies	Adaptability	Task Efficiency and Support Resources	Responsiveness and Task Relevance
5	[24]	Ambient Sound Classification	Microsoft HoloLens Mixed Reality Device	Availability	Support Resources	Accessibility and Context Awareness
		Directional Sound Detection	Sound Classification Algorithm	Quality	Clarity of Instruction	Feedback and Responsiveness
		Visual Cues for Sound Alerts	Spatial Audio Technology	Accessibility	Visual Design	Consistency and Cognitive Load Reduction
		Sound Source Localization in Mixed Reality	Visual Notification System	Adaptability	Clarity of Instruction	Affordance and Task Relevance
		Customizable Sound Sensitivity	Adjustable Sensitivity Controls	Acceptability	Ease of Use	Personalization and User Control

6	[10]	Augmented Mask Display	Speech-to-Text Processing Unit	Accessibility	Clarity of Instruction	Accessibility and Responsiveness
		Real-time Speech-to-Text Conversion	Transparent or Semi-Transparent Display on Mask Surface	Quality	Visual Design	Intuitiveness and Cognitive Load Reduction
		Text Overlay with Adjustable Font Size and Positioning	Battery-Powered Display Module	Adaptability	Visual Design	Personalization and User Control
		Personalized Captioning Settings	Adjustable Captioning Display Settings	Adaptability	Ease of Use	Aesthetic and Simplicity
7	[11]	Visual Narratives	Sign Language Interpreter Component	Accessibility	Support Resources	Accessibility and Cognitive Load Reduction
		Sensory Substitution	Haptic Feedback System	Adaptability	Interactivity	Affordance and Feedback
		Haptic Feedback	Tactile Models and Replicas	Quality	Engagement	Intuitiveness and User Control
		Sign Language Integration	Mobile Applications with Accessibility Features	Availability	Support Resources	Accessibility and Scalability
8	[17]	Visual Learning	Avatars Based	Accessibility	Learning Progression	Accessibility and Intuitiveness
		Sign Language Integration	AR Integration	Adaptability	Engagement	Accessibility and Context Awareness
		Interactive 3D Environment	Interactive Learning Modules	Quality	Interactivity	Affordance and User Control
		Gesture Recognition	Touch and Gesture-based Interaction Controls	Accessibility	Ease of Use	Affordance and Feedback
		Real Time Feedback	Customizable Content for Individual Needs	Adaptability	Learning Progression	Personalization and Cognitive Load Reduction
9	[15]	3D Avatar for Sign Demonstration	3D Avatar for Sign Demonstration	Accessibility	Support Resources	Accessibility and Intuitiveness
		HoloLens	Microsoft HoloLens	Availability	Engagement	Context Awareness and Scalability
		Gesture Recognition	Gesture Recognition	Quality	Ease of Use	Affordance and Feedback
		Gamified Learning Activities	Gamified Learning Activities	Acceptability	Rewards	Engagement and Learnability
		Customizable Learning Paths	Customizable Learning Paths	Adaptability	Learning Progression	Personalization and Cognitive Load Reduction
10	[7]	Customizable Avatars	AI-driven Sign Generation Module	Adaptability	Engagement	Personalization and Accessibility
		Real-Time Sign Language Generation	Voice Generation System	Accessibility	Support Resources	Responsiveness and Feedback
		Voice Synthesis for Spoken Communication	Customizable Avatar System	Quality	Ease of Use	Accessibility
		User-Friendly Interface for Customization	User Interface Design Elements (e.g., Sliders, Color Pickers)	Acceptability	Visual Design	Intuitiveness and Aesthetic and Simplicity
		Feedback Mechanism for Sign Generation Accuracy	Feedback System for Real-Time Assessment	Quality	Learning Progression	Cognitive Load Reduction and Learnability

3.2. Comparative Analysis of Design Components

The components identified through the literature review were compared to determine the common components present in current MR models for HI users. Table 5 presents the results of this comparative analysis, highlighting the shared components across the analyzed models. Following this, the frequency of occurrence for each component within the existing MR models for HI users was calculated and is presented in Table 6. The model numbers referenced correspond to those listed in Table 4.

Table 5. Comparative analysis of design components

Model No/ Design Component	1	2	3	4	5	6	7	8	9	10
Avatar Based	/	/	X	/	X	X	X	/	/	/
Gesture Recognition Based	/	X	/	/	/	X	/	/	/	/
Sign Language Integration	/	/	X	/	X	X	/	/	/	/
Visual Based	/	X	/	X	/	X	/	X	X	X
3D Avatar Rendering	X	/	X	/	X	X	X	X	/	/
AR Integration	X	/	X	X	X	X	X	/	/	X
Speech Recognition and Captioning	X	X	/	X	X	/	X	X	X	X
Interactive Learning Modules	X	X	X	X	X	X	X	/	/	X
Real-Time Feedback System	X	/	/	X	X	X	X	/	/	/
Customizable Settings	/	X	/	X	/	/	X	/	/	/
Gamified Learning	X	X	X	X	X	X	X	/	/	X
Feedback Mechanism	X	/	X	X	X	X	X	X	/	/

Table 6. Summary of design components

Design Component	Frequency	Percentage (%)	Rating
Gesture Recognition Based	8	15.03	High
Sign Language Integration	7	13.21	Moderate
Customizable Settings	7	13.21	Moderate
Avatar Based	6	11.32	Moderate
Real-Time Feedback System	5	9.43	Moderate
3D Avatar Rendering	4	7.55	Moderate
Visual Based	4	7.55	Moderate
AR Integration	3	5.66	Moderate
Feedback Mechanism	3	5.66	Moderate
Speech Recognition and Captioning	2	3.77	Low
Interactive Learning Modules	2	3.77	Low
Gamified Learning	2	3.77	Low

3.3. Comparative Analysis of Design Elements

Table 7 shows the comparative analysis results of the elements of the MR model for HI. Then, the results were analyzed to identify the frequency of the occurrence of the elements in the existing MR model for HI as shown in Table 8. The following sections discuss the results of the comparative analysis on the design principles of the existing MR model for HI. The model numbers referenced correspond to those listed in Table 4.

Table 7. Comparative analysis of design elements

Model No/ Design Elements	1	2	3	4	5	6	7	8	9	10
Customizable Avatar Appearance	/	X	X	X	X	X	X	X	X	/
Gesture Recognition (Lip reading or Facial Expression)	/	X	X	X	X	X	X	/	/	X
Sign Language Context	/	X	X	/	X	X	/	/	/	/
Visual Cues	/	X	/	X	/	X	X	X	X	X
3D Sign Language Avatars	X	/	X	X	X	X	X	X	X	X
2D-to-3D Conversion	X	/	X	X	X	X	X	X	X	X
Real-Time Gesture Display	X	/	X	X	X	X	X	X	X	X
Feedback Loop for Gesture Accuracy	X	/	X	X	X	X	X	X	X	X
Customizable Display Options	X	X	/	X	X	X	X	X	X	X
Holographic Sign Language Avatar	X	X	X	/	X	X	X	X	X	X
Ambient Soung Classification	X	X	X	X	/	X	X	X	X	X
Directional Sound Detection	X	X	X	X	/	X	X	X	X	X
Sound Source Localization	X	X	X	X	/	X	X	X	X	X
Augmented Mask Display	X	X	X	X	X	/	X	X	X	X
Text Overlay with Adjustable Size	X	X	X	X	X	/	X	X	X	X
Personalized Captioning Setting	X	X	X	X	X	/	X	X	X	X
Visual Narratives	X	X	X	X	X	X	/	X	X	X
Sensory Substitution	X	X	X	X	X	X	/	X	X	X
Haptic Feedback	X	X	X	X	X	X	/	X	X	X
Interactive 3D Environment	X	X	X	X	X	X	X	/	X	X
Customizable Learning Path	X	X	X	X	X	X	X	/	X	X
Voice Synthesis for Spoken Communication	X	X	X	X	X	X	X	X	X	/
User-Friendly Interface for Customization	X	X	X	X	X	X	X	X	X	/

Table 8. Summary of design elements

Design Elements	Frequency	Percentage (%)	Rating
Sign Language Context	6	18.18	High
Gesture Recognition	3	9.09	Moderate
Visual Cues	3	9.09	Moderate
Customizable Avatar Appearance	2	6.06	Low
3D Sign Language Avatars	1	3.03	Low
2D-to-3D Conversion	1	3.03	Low
Real-Time Gesture Display	1	3.03	Low
Feedback Loop for Gesture Accuracy	1	3.03	Low
Customizable Display Options	1	3.03	Low
Holographic Sign Language Avatar	1	3.03	Low
Ambient Soung Classification	1	3.03	Low
Directional Sound Detection	1	3.03	Low
Sound Source Localization	1	3.03	Low
Augmented Mask Display	1	3.03	Low
Text Overlay with Adjustable Size	1	3.03	Low
Personalized Captioning Setting	1	3.03	Low
Visual Narratives	1	3.03	Low
Sensory Substitution	1	3.03	Low
Haptic Feedback	1	3.03	Low
Interactive 3D Environment	1	3.03	Low
Customizable Learning Path	1	3.03	Low
Voice Synthesis for Spoken Communication	1	3.03	Low
User-Friendly Interface for Customization	1	3.03	Low

3.4. Comparative Analysis of Design Principles: Assistive Technology (AT)

Table 9 presents the findings of the comparative analysis of AT design principles. Then, Table 10 provides an analysis of the frequency with which these principles occur.

Table 9. Comparative analysis of AT design principles

Model No/AT Design Principles	1	2	3	4	5	6	7	8	9	10
Accessibility	/	/	/	/	/	/	/	/	/	/
Adaptability	/	/	/	/	/	/	/	/	/	/
Acceptability	/	/	/	/	/	X	X	X	/	/
Affordability	X	X	X	X	X	X	X	X	X	X
Availability	X	/	X	X	/	X	/	X	/	X
Quality	/	/	/	/	/	/	/	/	/	/

Table 10. Summary of AT design principles

AT Design Principles	Frequency	Percentage (%)	Rating
Accessibility	10	24.39	High
Adaptability	10	24.39	High
Quality	10	24.39	High
Acceptability	7	17.07	Moderate
Availability	4	9.76	Low
Affordability	0	0	Low

3.5. Comparative Analysis of Design Principles: Empathic Design (ED)

Table 11 displays the outcomes of the comparative analysis of ED design principles, whereas Table 12 presents an analysis of the frequency with which these principles appear.

Table 11. Comparative analysis of ED design principles

Model No/ ED Design Principles	1	2	3	4	5	6	7	8	9	10
Clarity of Instruction	/	X	/	X	/	/	X	X	X	X
Ease of Use	/	/	/	/	/	/	/	/	/	/
Engagement	/	X	X	/	X	X	/	/	/	/
Interactivity	/	/	/	/	X	X	/	/	X	X
Learning Progression	X	/	X	X	X	X	X	/	/	/
Rewards	X	X	X	X	X	X	X	X	/	X
Support Resources	/	X	X	/	/	X	/	X	/	/
Task Efficiency	X	/	X	/	X	X	X	X	X	X
Visual Design	/	/	/	X	/	/	X	X	X	/

Table 12. Summary of ED Design Principles

ED Design Principles	Frequency	Percentage (%)	Rating
Ease of Use	10	22.22	High
Engagement	6	13.33	Moderate
Interactivity	6	13.33	Moderate
Support Resources	6	13.33	Moderate
Visual Design	6	13.33	Moderate
Clarity of Instruction	4	8.89	Moderate
Learning Progression	4	8.89	Moderate
Task Efficiency	2	4.44	Low
Rewards	1	2.22	Low

3.6. Comparative Analysis of Design Principles: Visual Interaction (VI)

Table 13 displays the results of comparative analysis of VI design principles, while Table 14 depicts the analysis of the frequency of their occurrence.

Table 13. Comparative analysis of VI design principles

Model No /VI Design Principles	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Consistency	/	X	/	X	/	X	X	X	X	X
Feedback	/	/	/	X	/	X	/	/	/	/
Visual Hierarchy	/	X	/	X	X	X	X	/	X	X
Affordance	/	X	/	/	/	X	/	/	/	X
Aesthetic and Simplicity	X	X	X	X	X	/	X	X	X	/
User Control	/	X	/	/	/	/	/	/	X	X
Accessibility	/	/	/	/	/	/	/	/	/	/
Flexibility and Efficiency of Use	X	X	X	X	X	X	X	X	X	X
Error Prevention and Recovery	X	/	X	X	X	X	X	X	X	X
Learnability	X	X	X	X	X	X	X	X	/	/
Context Awareness	X	/	X	/	/	X	X	/	/	X
Trustworthiness	X	X	X	X	X	X	X	X	X	X
Cognitive Load Reduction	/	X	/	X	/	/	/	/	/	/
Responsiveness	X	X	/	/	/	/	X	X	X	/
Task Relevance	X	X	X	/	/	X	X	X	X	X
Personalization	/	/	/	X	/	/	X	/	/	/
Discoverability	X	X	X	X	X	X	X	X	X	X
Engagement	X	X	X	X	X	X	X	X	/	X

Table 14. Summary of VI Design Principles

VI Design Principles	**Frequency**	**Percentage (%)**	**Rating**
Accessibility	10	12.5	High
Feedback	8	10	High
Cognitive Load Reduction	8	10	High
Personalization	8	10	High
Affordance	7	8.75	Moderate
User Control	7	8.75	Moderate
Context Awareness	5	6.25	Moderate
Responsiveness	5	6.25	Moderate
Consistency	3	3.75	Low
Visual Hierarchy	3	3.75	Low
Aesthetic and Simplicity	2	2.5	Low
Learnability	2	2.5	Low
Task Relevance	2	2.5	Low
Error Prevention and Recovery	1	1.25	Low
Engagement	1	1.25	Low
Trustworthiness	0	0	Low
Discoverability	0	0	Low
Flexibility and Efficiency of Use	0	0	Low

Based on the results discussed, a list of design components, elements, and principles grounded in assistive technology (AT), empathic design (ED), and visual interaction (VI) was identified, successfully achieving the first objective.

3.7. Initial Mixed Reality Model for Hearing Impaired Based on AT, ED and VI Design Principles

Then, to achieve the second objective, the initial MR model for HI people based on AT, ED and VI were designed as shown in Figure 3.

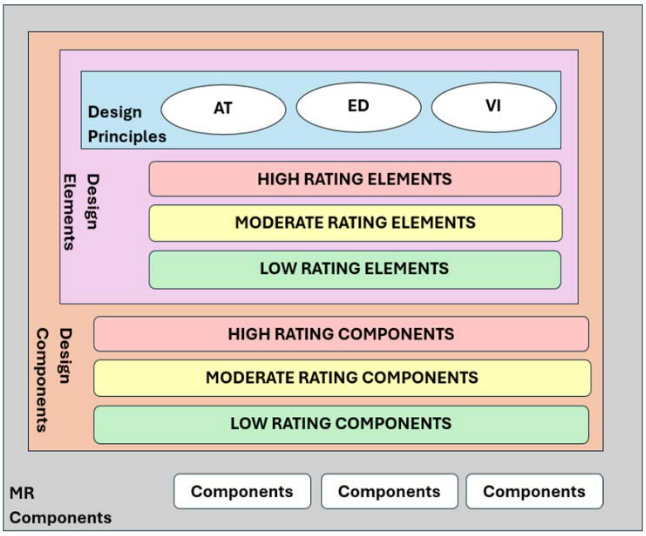

Figure 3. Initial mixed reality model for hearing impaired based on AT, ED and VI design principles

The findings from the comparative analysis were used to design the initial model, which is structured in four layers: design principles (blue layer), design elements (purple layer), design components (orange layer), and mixed reality (grey layer). Each layer's elements were derived from the comparative analysis results, categorized using a frequency table with high ratings (red elements), moderate ratings (yellow elements), and low ratings (green elements).

The core components of the proposed MR model are the central layer which outlines the design principles of AT, ED and VI. Then, the next layer is the design elements which are the specific features that support the design components layer to develop the MR for intended users. This initial MR model effectively integrates design principles, components, and elements to form a cohesive MR model tailored to the needs of HI users. It ensures accessibility, engagement, and usability while leveraging cutting-edge technology and empathetic design approaches.

4. Conclusion

The primary goal of this research is to develop a Mixed Reality (MR) model that incorporates assistive technology (AT), empathic design (ED), and visual interaction (VI) principles, tailored to the needs of individuals with hearing impairments. To achieve this, a literature review and comparative analysis are essential to examine existing MR solutions for the hearing impaired currently available in the market, identifying the components, elements, and design principles for the proposed MR model. In this context, the paper effectively addresses one of the research questions: "What are the components, elements, and design principles of the proposed MR model based on AT, ED, and VI for people with hearing impairments?" Future work will involve expert reviews and the participation of actual users in the model development process. Once completed, this model will serve as an ongoing resource for developers to create more MR applications for hearing-impaired users, fostering innovation in MR development in line with Industry 4.0.

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