From Skepticism to Acceptance: A Qualitative Study on the Dynamics of Elderly Engagement with Mixed Reality

Jessica Sehrt
Frankfurt University of Applied Sciences
Frankfurt am Main, Germany
jessica.sehrt@fb2.fra-uas.de

Ebony Mbamara
Frankfurt University of Applied Sciences
Frankfurt am Main, Germany
ebony.mbamara@stud.fra-uas.de

Mustafa Rafati
Frankfurt University of Applied Sciences
Frankfurt am Main, Germany
mustafa.rafati@stud.fra-uas.de

Valentin Schwind
Frankfurt University of Applied Sciences
Frankfurt am Main, Germany
valentin.schwind@fb2.fra-uas.de

ABSTRACT

As our society ages and technology becomes increasingly omnipresent, the use of Mixed Reality (MR) in private and health-related domains inevitably encounters the older population. This intersection presents unique challenges and opportunities for the integration of MR technology into the lives of elderlies. We conducted a qualitative study (N=7) using think-aloud interviews to gain in-depth insights into the usage of MR devices by elderly people. Using thematic analysis we identified barriers and facilitators for elderly engagement with MR: emotional response, ergonomics and handling, utility, learning competence, and acceptance. Our findings highlight the roles of timing, responsiveness, and skepticism towards the technology, which can act as a deterrent to the participation of elderlies. We contribute with a refined understanding of the elderly's interaction with MR and recommendations for elderly-centric MR technology adoption.

CCS CONCEPTS

• **Human-centered computing → Interaction devices**; **Virtual reality**; **Empirical studies in accessibility**.

KEYWORDS

Mixed Reality, Aging and Technology, Interaction Design, Ergonomics, Accessibility

ACM Reference Format:
Jessica Sehrt, Ebony Mbamara, Mustafa Rafati, and Valentin Schwind. 2024. From Skepticism to Acceptance: A Qualitative Study on the Dynamics of Elderly Engagement with Mixed Reality. In *Proceedings of Mensch und Computer 2024 (MuC '24), September 01–04, 2024, Karlsruhe, Germany*. ACM, New York, NY, USA, 16 pages. https://doi.org/10.1145/3670653.3670666

MuC '24, September 01–04, 2024, Karlsruhe, Germany

ACM ISBN 979-8-4007-0998-2/24/09
https://doi.org/10.1145/3670653.3670666

1 INTRODUCTION

The emergence of Mixed Reality (MR) technology has initiated a transformative era in human-computer interaction, offering immersive experiences that blend physical and digital worlds. MR technology, as a multimodal medium, presents various sensory and physical challenges [27, 56, 65, 73]. Simultaneously, its adaptive architecture makes MR systems particularly effective at overcoming barriers related to physical functions and cognition [1, 10, 18]. Therefore, MR technology has gained popularity in various fields, especially for use by the functionally impaired, ranging from rehabilitation [6, 16, 30, 64] to improved communication and cognitive enhancement [11, 12].

Due to demographic change, many countries are experiencing an aging population. This has created a growing demand for technologies that can enhance the lives of older individuals, promoting their independence and autonomy [23], and providing them with new engaging applications for sports [42] and rehabilitation [16, 30]. MR has emerged as a promising solution, offering new possibilities to improve the daily lives and social engagement of older people [22]. There is significant potential for the use of these technologies among older adults. MR devices, encompassing both augmented and virtual realities, present unique opportunities and challenges in the design and implementation of user interfaces, especially for older adults who often face physical and cognitive changes affecting their interaction with technology [53]. The significance of MR technology extends to enhancing the lives of the elderly by higher social connectedness through user-centered design [23], and autobiographical recalls in Virtual Reality (VR) for people with memory loss or even dementia [35].

Despite its promise, there is a lack of knowledge concerning the elderly's comprehensive engagement with MR devices, highlighting a need for research focused on their specific usability needs, the overall user experience [31], and age-friendly MR interface design [62]. Making MR more intuitive and natural to use could lead to MR devices being more familiar and motivating tools with assistive user interfaces for older individuals [13, 69, 78]. Evaluating the ergonomic design of MR devices for older adults requires identifying key usability factors and obstacles, considering both their physical and cognitive needs. The use of MR devices can be challenging for older individuals, as they are often not designed with their specific needs in mind, presenting them with important hurdles such as cable management or the complexity of the structure of the input devices (controllers) [33, 56]. The use of MR technology poses several challenges for older people, including vision impairments, reduced motor skills, and difficulties in navigating virtual environments [74]. These challenges may result in limited participation of older individuals in MR experiences, potentially excluding them from the associated benefits such as cognitive improvement and increased social interaction [56]. While there is limited research on the cognitive performance and well-being of older people in this context, numerous studies have explored the effects of MR in different domains. However, most of these studies have primarily focused on younger individuals and their reactions to MR, neglecting the impact on older generations [48].

In this qualitative user study, we investigated the feedback and behavior of seven elderly participants (from 69 to 82 years), performing a number of tasks to test both the hardware ergonomics and software usability of MR devices, ranging from hardware handling and software interaction tutorials to engaging with interactive sports applications. The goal of this research is the identification of general barriers before using and during interaction with MR technology by the elderly. We evaluated the usability of three different state-of-the-art MR devices (Microsoft HoloLens 2, Meta Quest 2, HP Reverb G2 Omnicept) and presented the barriers and facilitators imposed on the elderly by the interaction with these MR devices. Our findings indicate that how older adults interact with MR technology – affected by both the intuitive design of the user interface and the physical demands of the devices – significantly influences their willingness and ability to use these technologies. We inform the development of MR devices suitable for older users, and our findings can be beneficial in adapting software and hardware, paving the way for MR accessibility for people with low technology skills.

2 RELATED WORK

Research on MR technologies has highlighted their potential for health-related areas, remote communication, and empowering the autonomy of older people through early, self-organized use. Unlike other digital technologies, MR is uniquely capable of meeting the needs of older and functionally impaired people due to its direct interaction with human sensory perceptions. However, making these systems fully accessible to users with cognitive or physical impairments remains a challenge.

2.1 Challenges and Limitations in MR Technologies

The interaction patterns facilitated by MR's three-dimensional interfaces, while innovative, present notable limitations for individuals with motor or cognitive limitations, like the elderly. Despite MR's increasing popularity across various domains—such as human-computer interaction [9, 67, 70], entertainment [8, 19, 40], education [28, 29, 61], and healthcare [17, 44, 59]—issues like cable management, complex input device structures, and the need for interaction patterns tailored to specific needs persist. Research has quantified psychological and physiological responses to immersive environments, examining user presence [37, 38, 51], reactions to cyber sickness and latency [2, 56], and user motion adaptations, particularly in locomotion [27]. Studies have also identified barriers for neurodiverse users, focusing on sensory input challenges [12], and issues like text customization, eye strain, and anxiety [24, 57]. Additional barriers include the incompatibility of head-mounted displays (HMDs) with accessibility aids such as glasses, discomfort with VR headsets, agitation, unintentional damage in aged care settings, and misinterpretations of virtual as real [24]. The limitations of VR systems in supporting users with low vision [34, 78] have been addressed, alongside the critical need for adaptability in interactive experiences [72]. Research has also highlighted how immersive environments can elicit strong emotional reactions, both positive and negative [26], and how to promote positive emotions among elderly users with MR [7], primarily focused on the initial emotional impact without addressing how these emotional responses evolve during the usage of the devices, and identifying strategies to mitigate negative emotions.

2.2 Elderly Interaction in MR

The quality of user experience design of MR applications for the elderly is particularly determined by the extent to which satisfaction can be enhanced [1]. However, research often applies these technologies without addressing inherent barriers. These barriers often manifest systematically, particularly in terms of practical usability for individuals with disabilities [27], and persistently, like in issues related to social acceptance [65]. In MR applications, the use of controllers can be affected by longer reaction times combined with lower psychomotor coordination, making it challenging for elderly users to perform tasks that require high precision [73]. However, using an augmented reality-based training system to promote spatial visualization ability for the elderly has proven beneficial [39]. Cognitive decline typically includes a reduction in short-term memory, attention to detail, and the ability to learn an unfamiliar domain [75]. Therefore, a reduction in spatial cognition in MR applications is to be expected when the elderly use them [50, 65]. Cognitive training in the elderly using VR has shown to be effective [32]. Interaction with Augmented Reality (AR) has shown to be suitable for the elderly if new interaction patterns are designed that are tailored to their needs [76], but practical implementations tailored to the cognitive and motor abilities of older adults for reduction of usage barriers are still lacking. Related research has explored the role of adaptive interfaces in MR to improve usability, which could benefit intuitive and responsive interfaces, crucial for enhancing the user experience among elderly users [21].

2.3 Solutions and Future Directions in MR Technologies

Addressing the challenges identified, several studies have presented solutions ranging from the design of visual and physical features of input devices to encourage user interaction to the integration of familiar cues to facilitate the adoption of new technologies by the elderly [3, 33, 56, 76]. Familiarity, perceived usefulness, and social influence [66, 71] play significant roles in the acceptance of new technologies like MR by the elderly. Understanding how these perceptions are shaped is crucial for fostering and maintaining a positive attitude towards MR technologies. Furthermore, the use of MR in therapeutic interventions showcases its potential to significantly impact the daily lives and rehabilitation processes of the elderly and functionally impaired [25, 45, 63, 64]. Yet, a systematic and methodical approach to the evaluation and design of assistive MR systems is lacking. Our work aims to contribute to this field by focusing on user experience design [1] and the development of barrier-free MR applications that are accessible and beneficial to all users, particularly the elderly and functionally impaired. The use of virtual environments is increasingly the focus of numerous therapeutic procedures for elderly and functionally impaired persons [16]. Therapeutic interventions are thereby supported and enhanced over a longer period of time. These technologies also have the potential to facilitate and enrich the overall daily lives of elders and people with disabilities. It is believed that immersive environments (three-dimensional environments that enclose the subject), such as those provided in MR, can create a particularly strong sense of "presence" [63]. Oftentimes, guidance or assistance is needed when elderly users are confronted with MR scenarios. A study that focused on supporting older and impaired persons through a virtual assistance system showed great success [45] by projecting virtual real-time path-breaking content in front of them. This approach effectively guided them while maintaining their autonomy during the use of rehabilitative systems or light exercise. The use of VR to assist in performing movements has shown that by combining the benefits of indoor and outdoor activities, the desire to exercise can be promoted, particularly in the elderly [25].

2.4 Summary

The potential of MR technologies to improve the quality of life for elderly and functionally impaired individuals is clear and increasingly recognized. However, significant limitations in MR interfaces, such as complex input devices, highlight the need for usability and social acceptance research for users with motor or cognitive impairments. For elderly users, the importance of designing MR applications that consider cognitive decline and reduced psychomotor coordination suggests the integration of familiar cues to enhance their interaction experience. Future solutions propose redesigning input devices to be more user-friendly and utilizing MR for therapeutic interventions to improve the daily lives and rehabilitation processes of the elderly and functionally impaired.

3 METHODOLOGY

3.1 Study Design

We used a qualitative research approach to answer our research questions. While participants were interacting with the various MR devices, we employed semi-structured interviews, the think-aloud method, video observations, and additional subjective questionnaires. This allowed us to gain comprehensive insight into the challenges and barriers experienced by older individuals when using these technologies. The factors of our experiment were the different types of MR devices tested, varying in design and user interface. Based on the initial questions and the literature review, we identified the following research questions:

> *RQ 1: What are the physical barriers to using Mixed Reality devices, and how do they relate to the physical impairments of older users?*

> *RQ 2: What are the mental barriers preventing older individuals from using Mixed Reality devices?*

> *RQ 3: Are there systematic facilitators during the use of Mixed Reality devices by older individuals?*

It should be noted that the focus of our qualitative research was not to document the process of introducing older people to the technology, but rather to intensively experience all potential obstacles and interaction difficulties. Thus, the researchers only intervened to ensure the continuation of the study. This methodological approach, although time-consuming and potentially frustrating for the participants, enabled a profound understanding of the specific challenges and barriers of using mixed reality technology that may not have been apparent to technology-savvy users.

3.2 Mixed Reality Devices

The three different devices for our study were chosen due to their distinctive features and capabilities that align with our research objectives (see table 1), allowing us to explore the diverse aspects of user engagement and interaction within AR and VR environments, and to cover a wide spectrum of MR experiences. We chose two VR HMDs, distinctive in resolutions and functionalities, and one AR HMD. One VR HMD is PC-driven, connected via cable, with integrated biometric sensors, and the other is a standalone VR HMD. All three HMDs are the latest models in their respective series. With this setup, we aimed to present a broad overview of existing consumer devices and technologies to illustrate the difference between VR and AR as well as between controller-based and hand gesture-based interaction with the 3D environments.

The **Microsoft HoloLens 2 (HoloLens2)**, launched in 2019, was chosen for its advanced MR capabilities, allowing for the projection of holograms into the real world, thereby creating an augmented reality experience. It offers a variety of applications as well as enterprise-capable applications that can be controlled by interactions through gestures (as well as voice and gaze, which we did not present), coupled with its ergonomic design for increased comfort and an extended field of view.

The **Meta Quest 2 (Quest2)**, released in 2020, was selected for its superior VR experience, highlighted by its higher resolution, improved performance, and immersive experience facilitated through its use as a standalone HMD with controllers. The six degrees of freedom for tracking without external sensors, and the device's compatibility with a broad spectrum of VR games and applications further underline its suitability for our research.

Lastly, the **HP Reverb G2 Omnicept Edition (Reverb2)**, released in 2021, stands out due to its state-of-the-art sensor system to capture biometric data (integrated sensors measure muscle movement, gaze, pupil size; we presented pulse data to the participants) in real-time, and along with its compatibility with various VR platforms, makes it a valuable tool for examining the implications of VR technology in gaming, training, and medical applications. It also provides a high-resolution display. Still, these features come with the cost of being PC-driven via a cable, and we were interested in whether this could impose a potential limitation on the participants of the study.

(a) Microsoft HoloLens 2 (b) Meta Quest 2 (c) HP Reverb G2 Omnicept

Figure 1: The three devices Microsoft HoloLens 2, Meta Quest 2, and HP Reverb G2 Omnicept were evaluated in our study.

All three MR devices are available in a uniform size and are adjustable. According to the manufacturers, the HoloLens2 and the Quest2 are suitable for people who wear glasses. Additionally, the Quest2 package includes a spacer for glasses. As indicated in Table 1, the Reverb2 is the heaviest and largest HMD. Another disadvantage is that the device can only be used with a cable. However, this device offers the user the highest resolution and additional features, such as the collection of biometric data. In contrast, the Quest2 has the lowest weight and allows for wireless use. The HoloLens2, as an AR HMD, offers a fundamentally different technology from the two VR HMDs.

Table 1: Technical Data of the three devices.

Device	**HoloLens2**	**Quest2**	**Reverb2**
Weight	566 g	503 g	722 g
Dimensions (cm)	N / A	19 x 10 x 14	10 x 25 x 29
Resolution (px/eye)	1440 x 936	1832 x 1920	2160 x 2160
Display	Waveguide	LCD	LCD

3.3 Procedure

Our study was conducted in person in our lab facilities. The study took place in a controlled test environment to manage environmental conditions. The room was furnished with a desk and two chairs, on which a laptop connected to two monitors was placed. The participants' view through the MR devices was projected to a monitor to allow the experimenter to track the progress of the interaction. At the other end of the room, a camera was positioned to record the entire session.

Our research procedure began with a structured yet flexible approach, employing a semi-structured protocol. After handing out the consent form, participants were given a brief introduction to the topic. The participants were informed about the purpose and objectives of the study before it began. To compensate for any knowledge gaps, basic terminology was explained to the participants. Additionally, questions about experiences with VR and AR and reservations about technologies were asked. We included an initial hardware evaluation phase, clearly distinguishing between participants' impressions of the MR devices as physical objects and their experiences using the devices' software. This distinction allows for a more nuanced analysis of usability, encompassing both the tangible and intangible aspects of user interaction with MR technology. Additionally, the order of the devices was randomized to minimize potential impacts on the results. The procedure unfolded as follows:

(1) **Initial Hardware Evaluation:**
After receiving the Mixed Reality (MR) devices, participants first examined them without activation, sharing initial thoughts on appearance, size, and ergonomics. This step sought to understand immediate responses to design and build, highlighting hardware design's role in user acceptance and comfort.

(2) **Device Interaction and Tasks:**
Participants were introduced to three MR devices: HoloLens2, Quest2, and Reverb2. Before interacting with the devices, body mapping forms were administered to identify any preexisting physical complaints. The sequence of device presentation was randomized to avoid order effects. Participants then proceeded with the following tasks to assess usability and interaction experience with the devices' software:
- Independently download and install an application.
- Go through the recommended tutorial for basic device interaction.
- Engage with an interactive sports application.

The pure usage time of each device lasted about 25 minutes. During these interactions, participants were continuously interviewed, and think-aloud protocols were encouraged to provide real-time insights into their thought processes, challenges, and perceptions. This approach aimed to capture a more in-depth understanding of the user experience, allowing researchers to gather qualitative data on participants' interactions with both the hardware and software components of each device. In case a participant did not make progress, an experimenter was always available to help. Initially, participants were provided with verbal instructions to facilitate progression. In instances where verbal guidance proved insufficient, experimenter intervention included temporarily assuming control to navigate through the subsequent step. All applications used were commercially available, ensuring relevance to everyday user experiences. Before the initial session with the first device, participants completed a pre-use body mapping form. After each session, participants completed the Equipment and Display Questionnaire (EDQ) and System Usability Scale (SUS) questionnaires, and a post-use body mapping form, and participated in an interview to discuss their experiences. The procedure was repeated for the remaining devices in randomized order. Following all device interactions, a final questionnaire session was conducted to directly compare the devices and gather preferences and feedback.

3.4 Participants

We recruited seven older adult participants, including three females and four males. The mean age of the participants was 76.29 (*SD* = 4.45) ranging from 69 to 82 years. All participants were living independently in their own homes and their education ranged from primary school degree to Doctorate. In table 2 we report on their experience with MR from the post-experiment interview, which might be correlated with their prior exposure to computing devices that might affect their abilities to interact with our MR devices. While three participants disagreed, four participants agreed that they had previously used an MR device before; however, they did not interact with the device themselves but rather were handed it to view predefined content. Participants were recruited via institutional emailing lists, partnering institutions of our research center, and word-of-mouth referrals. The study received ethical clearance according to our institution's regulations and hygiene protocols for user studies.

Table 2: Participants' demographics for the interview study [P stands for participant]. Concerning the MR Experience "yes (passive)" indicates no interaction.

ID	Age	Gender	Education (Degree)	Family status	Mixed Reality Experience
P1	82	m	Secondary	Widowed	no
P2	69	w	Primary	Divorced	no
P3	81	w	Doctorate	Widowed	yes (passive)
P4	76	w	Primary	Widowed	yes (passive)
P5	73	m	Master	Widowed	yes (passive)
P6	78	m	Primary	Married	yes (passive)
P7	75	m	Bachelor	Married	no

3.5 Data Analysis

Data were analyzed using an inductive approach for thematic categorization of participants' comments, followed by a deductive approach to answer the research questions. Using an inductive approach for thematic categorization first aimed to naturally surface patterns or themes directly from the data. This methodological switch emphasized a more open exploration of the data at the outset, allowing for the discovery of unexpected insights, which are then rigorously tested against the research questions through a deductive process.

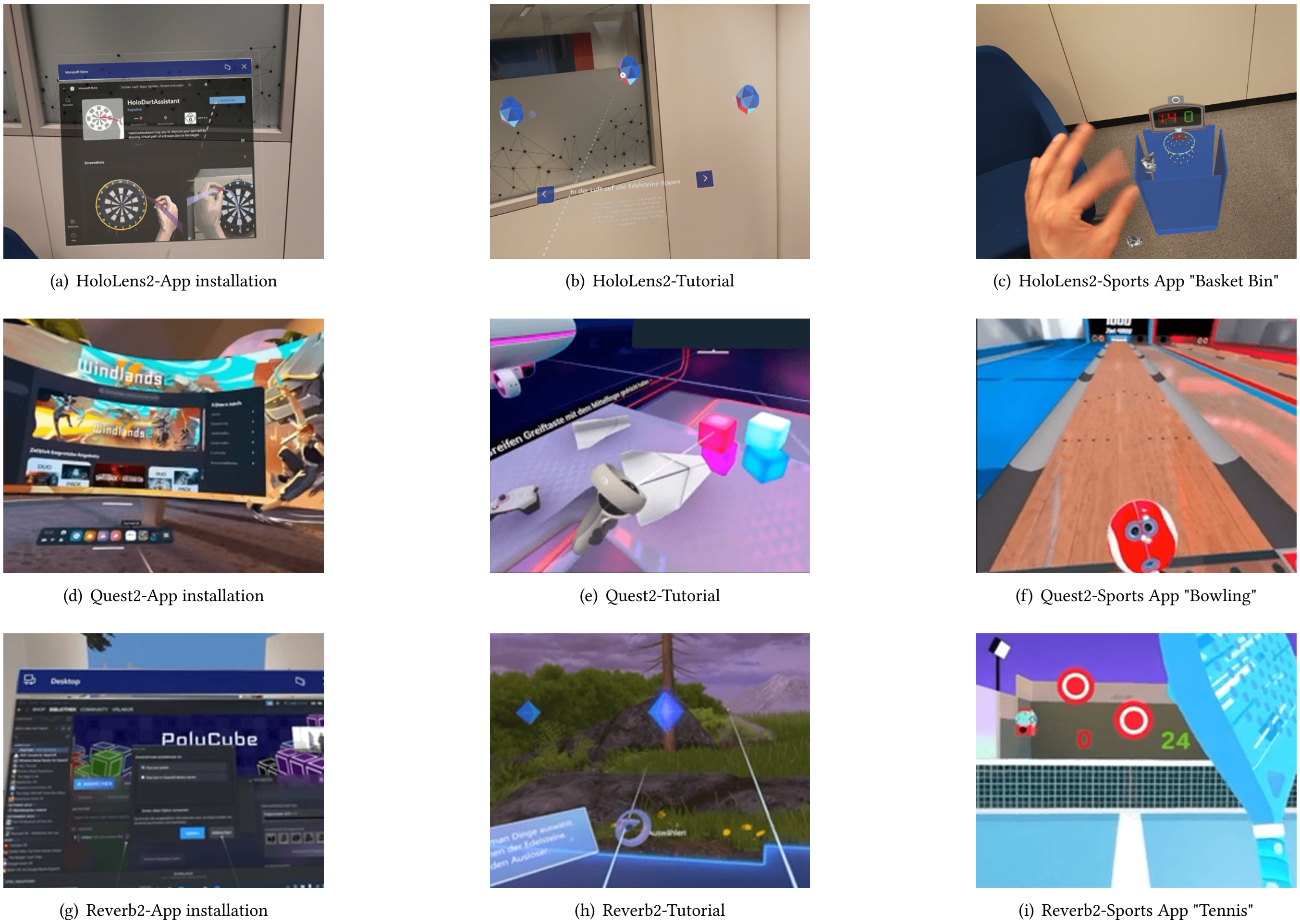
3.5.1 Thematic Analysis. We recorded 14.53 hours of video and audio data (on average 2.07 hours per participant, SD = 0.24 hours) and used thematic analysis to analyze our data. Two researchers first went through the data independently and open-coded the interviews. They met to discuss the initial codes and form a joint codebook. A third researcher was added for the third iteration to identify overarching categories. Video recordings were referenced as necessary to support this analysis. Open coding was followed by axial coding to integrate and refine the categories to form a cohesive narrative or theory. ChatGPT 4.0 [and plugins] were used to find and refine definitions, as recent research showed that these frameworks can be used to amplify the quality of thematic analysis [60, 77]. We repeatedly reworked and refined the coding by comparing the proposed solutions to our subjective coding analysis outcome.

3.5.2 Quantitative Analysis. To systematically evaluate the usability and user experience of MR devices, we employed some quantitative evaluations. The process of body mapping [58] was used to pinpoint areas of physical discomfort. Participants indicated on a diagram of a human body any discomfort experienced before and during device use, rating the severity on a scale from mild to severe in numeric values and color. The SUS [43], as a widely used tool to assess the overall user-friendliness of a system, involved asking the participants to rate the complexity, user-friendliness, functional integrity, consistency, and applicability of the devices on a scale from one to five. The EDQ [58] focused on the ergonomics of the HMDs in use, inquiring about physical discomfort, posture difficulties, and visual display issues.

4 RESULTS RELATED TO THE RESEARCH QUESTIONS

In our first research question, we wanted to find out what the physical barriers to using Mixed Reality devices are, and how they relate to the physical impairments of older users. Our investigation into the physical barriers encountered by older adults when using MR devices revealed surprising findings. Contrary to initial expectations that age-related physical limitations such as diminished vision would pose significant challenges, it was the timing and user interface responsiveness that emerged as the primary physical barriers. This suggests that the physical impairments commonly associated with aging were not as prohibitive as the technological limitations of MR devices themselves. Psychological concerns, particularly the fear of damaging their own glasses or expensive device equipment, also played a significant role in shaping user experience. Specifically, the gesture-based interactions with devices like the HoloLens2 were noted to be problematic, highlighting issues of responsiveness. The Reverb2 cable was mostly, yet not exclusively, recognized as hindering, as expected, and the complex layout of the controller buttons, aimed at users experienced with gamepads, also presented an initial challenge in device handling. This emphasizes the need for standalone functions in VR equipment and intuitive interaction paradigms for control units of the devices for older users.

In our second research question, we investigated the mental barriers preventing older individuals from using Mixed Reality devices. Our research identified two main mental barriers hindering the adoption of MR technology among older adults: perceived technological exclusion and the perceived age gap. These barriers cultivated a sense of detachment or estrangement from advanced technologies, with participants feeling as though MR devices were not designed with their age group in mind. This sense of alienation was compounded by experiences of difficulty and frustration when attempting to use VR glasses, leading to feelings of inadequacy and incompetence. Such perceptions not only diminished users' confidence in their ability to interact with MR technology but also



(a) HoloLens2-App installation

(b) HoloLens2-Tutorial

(c) HoloLens2-Sports App "Basket Bin"

(d) Quest2-App installation

(e) Quest2-Tutorial

(f) Quest2-Sports App "Bowling"

(g) Reverb2-App installation

(h) Reverb2-Tutorial

(i) Reverb2-Sports App "Tennis"

Figure 2: All tasks that participants went through during the procedure. First row: The participant views the tasks on Microsoft HoloLens 2: Independent App Installation [a], Tutorial [b], and Sports App "Basket Bin" [c]. Second row: The participant views the three tasks with the Meta Quest 2: Independent App Installation [d], Tutorial "First Steps" [e], and Sports App "Bowling" [f]. Third row: The participant views the tasks with the HP Reverb 2 Omnisept: Independent App Installation [g], Tutorial [h], and Sports App "Tennis", with pulse monitor display (not visible in screenshot) [i].

influenced their overall acceptance and willingness to engage with these devices. The findings suggest that mental barriers, rooted in perceptions of age-appropriateness and technological accessibility, play a critical role in shaping older adults' engagement with MR technologies.

Finally, we were interested in whether there are systematic facilitators during the use of Mixed Reality devices by older individuals, in our third research question. In addressing the facilitators that could enhance the MR experience for older adults, our study highlights several key factors. Notably, the accurate representation of physical objects, including hands and controllers, along with precise finger movements, significantly improved user interaction during the Quest 2 tutorial. This suggests that visual and interactive fidelity in MR environments can greatly aid in the learning process. Supportive representation and personal assistance were also identified as crucial facilitators, indicating the value of guidance and support in navigating new technological landscapes. Furthermore, the element of awe and novelty in experiencing new environments played a significant role in motivating older adults to overcome initial challenges and adapt to new interaction paradigms. However, it was also found that while AR offered the advantage of keeping surroundings visible, the poor quality of interaction in AR settings often hindered the learning process, in contrast to VR settings where the use of controllers facilitated a quicker adaptation. Emotional responses, including stress and mood, were also significant in influencing cognitive performance and decision-making, underscoring the complex interplay between emotional well-being and technological engagement among older users.

5 RESULTS OF THE THEMATIC ANALYSIS

The harmonized codes from the initial open coding process led us to overarching categories from the axial coding. We identified the usability dimensions and preoccupations of the participants. Through multiple iterations and discussions, under the lens of our research questions, the final process led to five overarching themes that seem to play key roles in the engagement of older individuals with MR technology. Those were: *Emotional Response, Ergonomics, User Experience, Learning Competence*, and *Acceptance*. The following will explain these and highlight central aspects, each supported by corresponding quotes.

5.1 Emotional Response

Both positive and negative emotional reactions towards the MR devices were expressed during the study. The most prominent negative feelings were despair, fear, and insecurity. Despair was especially noticeable when there were problems with operation, for instance, when the correct button or combination of buttons could not be found, when multiple attempts were necessary for the right timing, or when the task was unclear. Participants often became desperate after several unsuccessful attempts, thus requiring the motivational words of the observer to continue.

> *I say close, close! Damn. It doesn't even do that for me, oh man! (P4)*

> *This is driving me crazy! (P1)*

Glasses wearers were afraid for their glasses, fearing they might bend or scratch, when participants commented "But this doesn't work with the glasses. I'm afraid I might scratch my glasses with it." (P2), "I'm worried that my glasses are now bent." (P2), or "I'll take off my glasses first, otherwise they might break." (P7). During immersion, it happened that participants hit the wall with the controller. Surprisingly, participants were not afraid of hitting something. Upon inquiry, participants stated that the presence of an observer provided them with a sense of security. However, some participants were afraid of moving freely. Observations made it clear that this led to a restriction of the range of motion grid. It was observed that these individuals held their arms closer and more rigidly to the body and also took only small steps upon request. These individuals required increased assistance from the observer regarding physical positioning to fulfill the task. The representation of the virtual environment influenced the emotional state. A participant reported in one virtual environment the lack of "support" and in another, a feeling of security. The greatest sense of security was felt with HoloLens2, due to the visibility of the real environment.

> *It's up to me, this insecurity of standing in a room where I have no grip. It's the same as when I'm hiking in the mountains and then suddenly feel sick and sometimes have to give up. It's this spatial security. But that's my psyche. (P1)*

Another participant reported feeling insecure due to the high support pillars in the virtual environment and stated "It gives the impression of looking into a cave." (P2). Positive emotions were expressed through excitement and fun during use. Especially the visual representation of the environment amazed the participants: "That was fantastic!" (P1) [on the Sports App with the Reverb2]. Some even associated the environments with old memories such as a vacation, when they explained "I think I'm in the mountains now. Just miss the nettles jumping around. Yes, beautiful image, beautiful panorama, very nice." (P6). Particularly the sports activities were perceived positively and therefore commented on with "It was really fun." (P3), and "It's so exciting!" (P4).

5.2 Ergonomics and Handling

Physical impairments were divided into pre and post-complaints. Pre-complaints were initially independent of the use of mixed reality devices but can hurt the experience. The mentioned pre-complaints include visual impairments, back pain, nerve pain, hearing loss, sensitivity to weather, immobility, and vertebral fractures due to osteoporosis. Particularly, visual impairment was identified as an obstacle. Various forms of visual impairment and visual aids were recognized: astigmatism, glaucoma surgery, reading glasses, and progressive lenses. One participant reported that due to his visual impairment in the left eye, he occasionally has to squint to see clearly.

> *I think that if someone doesn't have this defect in an eye, it would be better. (P1)*

Wearing glasses in combination with a headset posed an additional problem. Especially for participants wearing progressive lenses, even small contact points with the glasses can distort vision.

> *It probably has to do with the glasses. Glasses wearers are always at a disadvantage in such cases. And it will be different for every glass wearer. You probably don't have problems. Any contact with the glasses with something else naturally shifts the perspective. So, glasses wearers will always have a bit of a problem. (P7)*

Hearing loss also posed an obstacle while completing tasks, evident as a participant stated, "I sometimes didn't understand it acoustically." (P1). Post-complaints are caused by using the devices or exacerbate pre-complaints. These include loss of concentration, dizziness, pressure on the glasses, and (increased) back pain. The loss of concentration combined with back pain was so significant for one participant that the study had to be continued on another day. He stated that he "...had back pain and had to concentrate and was distracted by my back pain. That was an additional issue. It was stupid. Sorry." (P1).

The strongest complaints were caused by back pain. Participants who reported back pain as a pre-complaint experienced increased pain. Another participant stated that the required movements also influenced the back pain (see Table 3).

> *It's way too fast. I can't do these quick movements, it hurts my back. (P4)*

Dizziness was also caused by using the devices, which led to the need for breaks in between. Moreover, dizziness can trigger fears of movement, which can be an additional hurdle. The participant complained that the dizziness is "simply caused by the glasses" referring to the tight fit of the VR glasses.

> *I don't want to turn around completely because I feel a bit dizzy. May I please sit down for a moment? Oh, it's terrible. It's extremely uncomfortable. (P2)*

A crucial factor here was the positioning of participants in the virtual environment. Four possible misalignments of the body were identified: too far to the right, too far to the left, too far forward, too far back. It was observed that participants were not aware of their misalignment. Additionally, gestures are a component of interaction with the virtual world, where unclear, slow, and tense movements were observed. Here, the physical fitness of the participants plays a decisive role. Physical fitness was noticeable through exhaustion, accuracy, reaction capability, and fine and gross motor skills. Features like device weight, display, and tracking were perceived as hindrances. One participant's face went "...all red from the effort. It's strenuous." (P1). Conversely, another participant described physical activity as "on a low level." (P3). Depending on physical fitness, the need to sit varied greatly. For many participants, especially long-standing caused back pain.

In handling the controllers, it was observed that there was confusion about the controllers' top and bottom sides, and the controllers were held in the wrong hand. Also, in handling, positioning plays a crucial role. The hand can be too far forward or too back in the VR environment, and the arm too high or too low. Furthermore, the positioning of fingers led to obstacles in use, when middle and index fingers did not lie over the corresponding buttons. A participant was forced to support the headset from below due to the tight fit of Reverb2 on the glasses and commented that he had "...to hold it. [If you let go, is it then too loose?] Yes, it slips down and also presses hard on my glasses. So that doesn't work. No, it's way too tight." (P1). The Reverb2 is also the heaviest of the three devices (see Table 1).

Thus, the device could only be operated with one controller. Due to the supporting posture of the arm, the participant experienced pain in the left shoulder (see Table 3). It was criticized that the weight pulls the headset down and presses too hard on the glasses or facial area. The design as a product feature elicited both positive and negative factors. A wired use was perceived negatively by the participants when they commented "It would be a failure for me if it's complicated with the computer." (P4), or "Of course, it's also something you can walk around with if it's not wired." (P3). A participant assumed someone was behind him when it was the cable on his shoulder. Another participant sees the advantage of the connection to the computer: "I'd say it's more of a plus because the range of functions naturally increases. If it works entirely autonomously like the other, then somehow the range of functions is a bit limited, potentially possible range of functions. It should have more variability." (P7). Associations like "astronaut helmet" (P4), "atomic mask" (P5), "bicycle helmet" (P6), or even "gas mask" (P5) were evoked by the design of the devices. The size and also the color of the device were named as relevant.

> *The design, if possible, a bit smaller, a bit nicer, more stylish, also the color - the white - black is more discreet, makes [it] look slimmer. (P5)*

It was observed that individual components, such as the wheel for adjustment of the focal distance, were recognized and intuitively used by the participants. The perceived ease of use greatly influenced the participants' evaluation. From observations, it was clear that operating with the hands posed a greater hurdle than operating the controllers. The controllers posed a challenge, "because the buttons were new" (P7), but "..the functions are clear." (P7). Regarding hand operation on HoloLens2, a participant said: "Even if the operation is simpler, I have my difficulties here." (P6). Typing with fingers was generally found annoying by the participants on HoloLens2.

> *I found it easier with the controllers. This fingertip typing is sometimes quite a search. (P1)*

The quality of all three displays generally convinced the participants. It looks "real" (P6, P5), and was described by the participants as "great" (P2, P3, P4) and "beautiful." (P2, P4, P1). Furthermore, an application on Quest2 was praised by a participant because of the "perfect animation" (P5). However, the display could also impair the experience. The display contributed to overwhelming one participant. As a reason, he mentioned "It might also be because of the decor" (P1). In a VR environment, too many objects could lead to confusion and distraction from the actual task. The participant also perceived that the strain on his eyes was different from the real world while stating "...as if I'm in a planetarium because I'm staring all the time" (P1). In an AR environment, however, the "3D effect is not so strong" (P1). Still, also seeing the real and familiar environment gave the participant a sense of security. Moreover, the display could serve as support for the task. "It even lights up" (P4). For many participants, clicking on specific buttons or interactive fields posed an obstacle. A visual response made it easier for participants to operate.

> *I wasn't quite clear on how to activate the individual fields or when they were active (P2)*

> *And I also don't notice whether he's got it now. So the grey box is missing or some kind of sign. (P2)*

The visual display of controllers or hands proved to be helpful for participants in interactions (see Figure 3). For example, a participant noticed through the display that she was holding the controllers in the wrong hand. However, visual aids must be recognizable. Especially with HoloLens2, participants had difficulty following the tracking of their hand on the display because the representation was not clear enough. They tried to follow the visual aid, but the cursor was too small: "I don't see a point." (P6), or not recognizable: "But that's also because the color is very light." (P3). Another product feature that was pointed to as hindering in HoloLens2 was the field of view. To open the menu on HoloLens2, participants had to stretch their arms forward and tap on the inside of the wrist. This presupposes that the wrist is recognized by the sensors and that the hand is within sight. The problem for participants was that they could see their wrists through the glasses even outside the field of view and therefore did not understand why the menu hologram did not appear on the wrist.

> *Now it has recognized my press, but again nothing happens. (P5)*

Tracking, especially with HoloLens2, posed an obstacle. Participants complained that tapping was not recognized and the device's response was too slow. Tapping on the virtual display was compared by participants to using a smartphone: "So on the phone, it's different. I have to say that. It's still too difficult to operate in that regard." (P4).

In the course of observation, participants made suggestions for improvement regarding the use of mixed reality devices. A participant commented on the design of the devices to have them smaller and lighter, and "...just for the eyes, without headgear, like glasses, like a diving mask." (P6).

5.3 Utility

Proper timing during interaction and for interface operations and user-interface responsiveness posed a significant hurdle, with prior technical experience with modern technologies positively influencing competence. Interactive situations where there was a mismatch or lack of synchronization between expected or natural timing patterns of the perception of sensory inputs, like finger movement with the anticipated tempo or pattern in which the user-interface elements responded, were a constant recurring cause of frustration.

The representation of the participant's embodiment highly affected the perceived accessibility of the user interface, especially the buttons. Visual perception is closely connected to the body and thus influences the operation of parts of the body, in the case of VR the virtual hands, or in the case of AR the hand extensions like ray casts. For example, the Oculus button on the controller of the Quest2 had to be pressed to reach the general menu of the device's user interface. In these cases, the controller is visually represented on the display, but not the user's fingers. This posed an obstacle for all participants, necessitating the experimenter to press the button for them. While participants were in the Tutorial of the Quest2, both the controller and the hands were represented in the embodiment of the user, which showed a huge advantage in the operation.

> *Yes, so I see the X and the Y. Oh, that below is the Windows sign? That's hard to recognize. How do I get there? I can't reach it at all. (P4)*

> *I can't press anything because I don't see my thumbs. (P7)*

Embodiments could be recognized in the applications as the controller, the controller with an artificial hand, the artificial hand, or the virtual object. Here, hands can be replaced by "gloves" or controllers or even disappear entirely. It is important to mention that the representation of hands does not depict the actual movement of hands and fingers but rather the controllers and their respective button functions. The different representations of hands in the virtual environment elicited varying reactions.

> *You have to move your hand quite differently than in reality. (P4)*

> *I didn't quite get along with these hands - although it's wonderful when these gloves appear and then the fingers that you should use light up. Then, of course, I just have to find the right button, which I still don't know. [...] So the grip button is still the one I feel but no longer see. (P4)*

The controllers as a reason for irritation were distinguished by a participant as follows, while he proposed an interaction similar to a ray cast with dwell function:

> *What's irritating anyway: You do have the haptic feedback that you're holding them in your hand, but the two virtual parts there, they don't belong to it. You can act with these lightsabers, but they are not the ones you press. (P4)*

In an AR environment, visual representation also led to irritation, as participants often confused the virtual hand, which serves as assistance, with their hand, even though their hand is visible in the AR environment.

> *It caused more confusion than help. (P3)*

Another participant pointed out the issue of accuracy and emphasized:

> *I'm an impatient person and if I have to juggle back and forth forever - Although I accept, you need a certain learning phase, also with the mouse, but it should be significantly shorter. (P5)*

A specific suggestion for change was to "...mark it [the circle] and then slide it in over a large area." (P5). This comment referred to the participant's difficulty in operating the user interface with the hand on HoloLens2. Another participant criticized the motion detection of the device and suggested, "that the motion leads to me catching it right away. And as you saw, I pressed all the time and nothing happened." (P4). Such improper timing was a major hurdle in operating all three devices. What is meant here is that buttons on the controller or the virtual display were not pressed at the correct point in time or for the required duration. At some points, the necessary duration was only a few seconds longer to trigger a different function than intended. For example, a participant wants to start an application and presses too long on the field:

> *...and it says to release? What does release mean again? [...] I can't as quickly as you mean. I can't do that. [talking to the device] (P4)*

Participants were aware that the impulse was not accepted as desired but did not know why. "It blinks every time somehow, but then still nothing happens. I don't understand. The beam turns blue briefly and then I let go." (P4). Multiple attempts and instructions from the observer were required for successful operation. It was observed that participants who initially did not receive support often did not vary the timing and relied on repetitive movements. This also applied to other required movements. "I figured out the trick that if I press briefly, then it goes immediately. I pressed too long before." (P1). Observations revealed that participants also unintentionally pressed a button continuously. Another problem was the delayed pressing of buttons when a combination of buttons was required.

5.4 Learning Competence

The participants' competence was particularly evident through their technical prior experience, the need for help, and the learning process. Some participants had already experienced VR. None of the participants had previously encountered AR. The extent to which the participants were generally familiar with modern technologies was also apparent in the study.

> *So with these apps and stuff. I don't have such a thing. I have such an old-fashioned phone. I don't have such a thing. Difficult topic, apps. (P1)*

> *A normal grandma like me, she doesn't know that. (P4)*

Moreover, it could occur that users had a basic understanding of how VR works, evident in the statement: "There's nothing to tap there. It's virtual" (P4). Conversely, for other participants, the smartphone is part of everyday life: "The stuff you need in the household" (P7). Tasks like downloading an app were not an obstacle for these participants. Familiarity with the interface made it easier for these participants to use the MR interface, "...since it's identical, in terms of look and feel, to the smartphone." (P5). Participants who were already familiar with the use of modern technologies like smartphones were able to navigate virtual environments more easily and quickly. In contrast, participants with lower technology affinity relied on the observer's assistance. Thus, they needed additional hints to complete tasks.

> *[And how did you try to deal with the problems?] By you helping. If I had been alone, I would have kept trying and eventually realized what was right. (P7)*

Particularly, new terminologies posed a hurdle, so it was often unclear which button was meant. It also happened that fields were clicked unintentionally. Often, participants were not aware why it "suddenly" worked after multiple attempts: "...it's by chance" (P7), "So it worked once, but next time... no idea" (P1). Observations showed that accuracy improved "bit by bit" (P1) with practice. Depending on the participant's competence, the *adaptation period* varied in length. However, all participants said they needed some time to learn the operation:

> *When I figured out that only these two buttons need to be pressed for bowling. Then it became easier. (P1)*

> *I figured out the trick that if I press briefly, then it goes immediately. (P1)*

Many participants emphasized that they had no experience with computer games and therefore needed an extended period of acclimatization: "...takes getting used to. I never played such games before on the computer. So I'm a bit inexperienced, but it's quite easy to learn things." (P3). The learning process could be facilitated by supportive representation: "A bit of practice, but luckily there's text here that I can read. But surely with practice, it's no problem, just like eventually learning what's left and right with a mouse." (P5). One participant suggested that the device (Quest2) should be adjusted to fit perfectly the first time so that only minor adjustments are needed. (P4)

5.5 Acceptance

Concerns or even fears were expressed that MR may become too dominant in the future, potentially neglecting real-world interests. These concerns could lead to elders being inhibited during use. During the study, various reservations regarding the use of mixed reality devices were recognized through the comments of the participants. Some participants expressed concerns that the use of MR systems might be problematic for children, as they could have difficulties distinguishing reality from fiction. A participant expressed it as follows:

> *I don't know how the little kids handle it, whether there are also difficulties in distinguishing reality from fiction. (P3)*

Another reservation expressed by participants is the potential addiction risk through the use of mixed reality devices. A participant expressed concern that some people might become addicted and live only in the virtual world (P7). Another participant emphasized the importance of interpersonal relationships and expressed concern that they could be lost through the use of MR systems.

> *I don't want to experience having to converse with a computer or marry a computer. We are human beings with flesh and blood and soul and spirit. That should be preserved. (P6)*

This general skepticism towards the devices, regarding whether it makes sense that they were developed, was accompanied by a distrust in one's abilities to use these devices themselves. Participants expressed a feeling of being the "wrong candidate" (P1) or "not being suitable" (P2) during device use. This seems to stem from age-related barriers and from the perception that technologies like MR glasses are primarily designed for younger generations who are more tech-savvy or accustomed to digital experiences. They felt that the technology was not intuitive for them, and tailored to the preferences of a different age group, leading to a sense of not belonging. This perceived *technology exclusion* was expressed through statements that one feels the technology is not designed for someone of their age or background, making them feel out of place or inadequate when trying to use it.

> *So, little by little, yes. But if you're technically gifted, it's probably easier. And unfortunately, that's not the case for me.... (P1)*

Statements like "Younger individuals who have grown up with advanced technology may find it easier to interact with [this device] than me as a senior who did not have exposure to such innovations during their formative years." (P1, P2, P3) highlight the impression of a potential divide between older and younger generations regarding technology adoption and acceptance, pointing to a perceived *generational gap*.

> *For older people who are not used to it, it's difficult. [What exactly is difficult?] Yes, because I try to understand it rationally, but somehow, I have to turn off my rationality... Turn off the intelligence to artificial. And that... I think I resist that. (P1)*

The statement about *leaving logic behind* indicates that the participant perceived the experience as something different from their conventional understanding of reality. As MR technology transported the older users to simulated environments, a *cognitive shift* is required as a willingness to embrace the virtual world as an extension of reality. Some of the participants struggled with that because this mental concept was unfamiliar to them. If participants experience *awe*, this was a big facilitator to overcome this hurdle. When the environment initially impressed the participant when entering the experience, the *cognitive shift* seemed a lot easier and participants responded with intrinsic motivation to engage even with unfamiliar user-interface elements.

> *Nice. That is my dream landscape. The two beams that are now going forward, what are they doing? (P3 entering the Reverb2 Portal) [You can use those to select and press things.]*

5.6 Summary

Five key factors influencing the engagement of older adults with MR devices were identified. In the category **Emotional response**, the users' feelings and psychological impacts from using the MR device became evident. This category captures the emotional and psychological reactions of participants, from awe and stress to various psychological barriers and experiences of feeling overwhelmed by too much information. It can range from joy and satisfaction to frustration and anxiety. Statements shed light on the capability of technology to make participants feel overwhelmed (technostress) or express fear of making mistakes but also feel awe. Situations in which positive or negative stress was expressed, and also instances where they felt bombarded with too much information, leading to confusion or discomfort, were the subject of this category. The **Ergonomics and Handling** category refers to the physical comfort and ease of using devices such as glasses and controllers. This encompasses the physical interaction with the product, including its design, comfort, ease of use, and any physical strain it might cause or alleviate. Participants' comments on the comfort or discomfort of the devices during use were a great example of how physical discomfort varies significantly with age and can be exacerbated by MR device use. Some participants had impairments like back pain and vision problems, which were particularly obstructive during the use of all three devices. Comments on the accuracy of device tracking or the usefulness of multimodal inputs were examples of this. The **Usability** category encompassed the overall satisfaction, intuitiveness, and engagement with the MR device. It focuses on the overall user experience, including the interface's responsiveness and clarity. This encompasses the overall experience of using the MR device, including interface design, ease of learning, intuitiveness, and the satisfaction of interaction. It's about how users engage with the MR device and their overall journey from novice to proficient users. Interaction and UX are central concepts. Feedback statements from this category showed how intuitive or confusing the user interface was, including frustration because of the lack of response of the interface (HoloLens2 pinch gesture). The **Learning Competence** category examined the ease of learning and users' development of proficiency with the MR device. Here, the focus is on the learning curve associated with the MR device and how users develop competence over time. This code looks at the resources and support provided for learning, as well as the challenges users may face in becoming proficient. Examples of these challenges included low learning curves or participants needing help to understand the technology. The category **Acceptance** encompasses attitudes towards MR technology, ranging from curiosity to reservations and exclusion. It examines how users accept the device into their lives and adapt to its introduction. It includes the willingness and the reservations to use the devices, including the shift in understanding from traditional to MR environments.

5.7 Proposed Use Cases

Discussions among participants revealed a variety of envisioned applications for AR and VR technologies. The preference for VR leaned towards gaming applications, while AR was seen as more suited for technical uses. One participant remarked on the HoloLens2, highlighting its unsuitability for gaming but potential usefulness for other purposes (P7). Regarding the likelihood of purchasing such technologies, participants were generally hesitant unless considered as a gift for younger family members. This sentiment was captured in two statements, one expressing willingness to indulge a grandchild's request (P3) and another indicating a decision could be influenced by a partner (P3).

The value of these devices was tied to their ability to offer convenience and comfort at least equivalent to current technology such as laptops or smartphones, as voiced by one participant (P5). Participants also discussed the potential of these technologies to address physical ailments. Suggestions included a device that corrects vision errors (P3) and an integrated acoustic device to aid hearing (P6). Views on additional health-related features like heart rate monitoring were mixed, with one participant dismissing it as an insufficient reason for purchase (P5), while another saw potential benefits in the medical field (P1). When imagining possible uses for AR and VR, participants cited a range of applications including cognitive enhancement (P1, P2), scientific research (P2), learning new topics (P2), exploring new places (P3, P4), and rehabilitation (P2, P4). Specific desires included experiencing underwater scenes without the physical burden of diving equipment due to health limitations (P4), using the technology for work efficiency or income generation (P5), selecting relaxing panoramas for leisure (P6), and learning or exploring from a sedentary position due to age or disability (P7, P3).

(a) Controllers in wrong hands. (b) Controllers handling corrected by own estimation. (c) Experimenter giving support.

Figure 3: Illustration of visual assistance through the display of hand-models in VR, from the initial mistake in controller handling to the user's self-correction, and assistance from experimenter by providing aid via holding participant's arm, when her spacial orientation was lost.

6 QUANTITATIVE RESULTS

The complaints of participants before the study (pre-complaints) and those caused by each device on average among all participants were evaluated by the body mapping questionnaire (see Table 3) and the SUS questionnaire (see Table 4). To conclude the devices, body mapping was also completed before using the devices, and any complaints not directly attributed to the use were excluded from the analysis. The results show differences in terms of the severity and type of pain, with HoloLens2 causing the most severe discomfort. Notably, the SUS score for HoloLens2 is also the lowest. Interestingly, all devices fall below the recommended value of 70, suggested as a threshold for the acceptance of technology (c.f. [4]). A value below 40 is considered an indicator of poor usability, which is the case for HoloLens2.

Table 3: Number of physical complaints from participants from the Body Mapping. The table provides information on the complaints of participants before the study and those caused by each device on average among all participants.

Condition	Body Part	mild	moderate	severe	Total
Pre-complaints	Back pain	2	2	0	4
HoloLens2	Back pain	2	1	1	4
	Wrist	1	0	0	1
Quest2	Back pain	1	1	1	3
Reverb2	Back pain	1	1	1	3
	Left shoulder	1	0	0	1

For a comprehensive analysis of physical impairments related to MR devices, the EDQ was used. The results from Table 4 indicate that particularly the virtual reality headsets, Quest2 and Reverb2, cause complaints around the head. Specifically, the placement of Quest2 on the head posed an obstacle for 43% of participants and led to physical discomfort. Adjustments were necessary even after the device was fitted, suggesting a general problem with the attachment to the head. For Reverb2, the weight, which is 30% heavier than Quest2, was the main reason for physical complaints. As indicated by Question 6, a higher number of participants reported that Reverb2 exerted pressure. Some of these problems could be due to incorrect fitting of the devices, potentially leading to increased pressure points. Moreover, it is important to note that the complaints reported in the EDQ were higher than in the body mapping. This could be because participants did not experience pain, but felt physical impairments (c.f. [58]). However, this might indicate that prolonged use could lead to increased impairments. Quest2 and Reverb2 are associated with impairments that can affect the user's posture. In particular, most users who used Reverb2 reported having difficulty moving their heads. This may be due to the wired use and the weight of the device. In contrast, users of HoloLens2 did not express any posture-related complaints due to the hardware. However, the response to Question 8 revealed that 43% were impaired due to system requirements. It became clear that not only the hardware but also the interaction with the system can pose a physical challenge related to ergonomic issues.

Table 4: Results of SUS Questionnaire.

HoloLens2	Quest2	Reverb2
35,357	63,214	60,357

The display is an important ergonomic aspect as it directly influences the user's visual experience. From the results, it was evident that problems related to the display also arose. Specifically, HoloLens2 had the most issues related to the display. 71% of participants found the field of view to be insufficient. However, it is interesting to note that the quality of the display itself does not pose a problem, as indicated by Question 12. The results are understandable since the field of view of HoloLens2 is significantly smaller compared to the other two devices. Moreover, HoloLens2 offers the lowest resolution. While Reverb2 provides the highest resolution, it does not stand out in the results compared to Quest2. Participants experienced difficulties operating all devices. Remembering the button layout as well as reaching and operating the buttons posed obstacles. Since HoloLens2 is operated without a controller, questions related to controllers refer to hand operation in this case.

Table 5: Results of EDQ Questionnaire.

HoloLens2	Quest2	Reverb2
Posture impaired by the system	Head discomfort	Head discomfort
Field of view too small	Head mounting	Weight
Difficulties in the operation	Difficulties in the operation	Head movement restricted
*	*	Difficulties in the operation

7 DISCUSSION

Our study combined data from qualitative insights from think-aloud protocols and semi-structured interviews, analyzed through video and text transcript evaluations, with body mapping, SUS, and EDQ. We investigated the categories of physical and mental barriers imposed on elderly users of three MR devices, and if there are structural facilitators during the use of the MR devices for this age group. We compared the MR devices to understand their strengths and weaknesses from the perspective of older users. The study revealed an interesting observation: responsiveness and timing were among the biggest barriers to technology adoption, with a perceived age gap exacerbating feelings of exclusion and inability to adapt to new technologies. Related research reports on the elderly generally having a positive attitude towards MR technologies [1], and showing a general acceptance of MR technologies [5, 55], which was evident in our study as well, despite several challenges.

Our findings highlight that perceived operational difficulty in handling the devices, physical discomfort, and emotional reactions may influence older adults' MR preferences, leading to a need for specialized devices with easier interfaces and adjusted content [18, 49, 76]. The Quest2, in particular, was preferred for its superior usability. Despite its heavier weight, HoloLens2 did not receive complaints about discomfort, suggesting that weight distribution may be more critical than the weight itself, but it was rated as the most uncomfortable device. While EDQ results indicated no complaints about display quality, the field of view of HoloLens2 was criticized, indicating the importance of this aspect in user comfort. Perceived difficulty depended on participant competence, with notable challenges in interface operation. Surprisingly, not only controller operation but also hand operation posed obstacles, with timing and button memory being central issues. This contrasts with previous studies recommending hand operation for older adults [73], though practical issues arose. Constructive features of Quest2 and Reverb2's controllers were similar, suggesting virtual interface design might explain differing evaluations, indicating user interface design impacts perceived operability.

Our main findings highlight the critical role of timing and responsiveness in technology adoption and engagement. Additionally, skepticism towards technology, particularly among older individuals, is identified as a significant barrier. This skepticism is often rooted in a perceived "technology exclusion," where the age gap is seen as a hindrance to their ability to engage with and adapt to new technologies. This belief in their own inability to adapt not only affects individual engagement but also contributes to a broader reluctance towards embracing technological changes. The experience of awe was already shown to be a facilitator in immersive video environments [20], which was also evident in our results. Aids by the system and the experimenter were effective, which points to the fact that an approach of semi-supervised learning [47] might be applicable for MR applications.

Participants expressed a desire for applications that cater to the needs of older adults, such as exploring landscapes, engaging in sports interactions, and learning new facts. Willingness to use MR technology might be closely tied to available applications. Participants were generally open to using MR technologies but questioned their practicality and everyday utility, underscoring the need for applications that meet older adults' needs, possibly using personalization of the content [18, 36]. Participants valued exploring beautiful landscapes, engaging in sports interactions, and learning new facts. Those with higher physical fitness preferred real-world experiences but were open to MR if real-world activities became inaccessible. Our findings show participants with lower physical fitness enjoy viewing landscapes in MR more, especially natural landscapes, which can evoke nostalgia [1]. Older adults can experience positive emotional well-being effects from VR experiences that evoke memories [73]. This preference underscores the importance of designing applications that are not only accessible but also relevant to their interests and capabilities. The study suggests that virtual experiences can evoke positive emotions and memories, especially among those with limited physical fitness, indicating the potential of MR to improve the quality of life for older adults.

7.1 Implications

During our evaluation, the precise calibration of gesture recognition—particularly the timing between touch initiation and release—was paramount, advocating for adaptive systems that accommodate the varied response times characteristic of older users, especially when it comes to mid-air gestures [14, 15]. In the realm of MR technologies, gestural and touch-based interfaces have emerged as promising avenues for enhancing the interaction experience of older adults [46], which underscores the potential suitability of these interaction paradigms for the elderly demographic, highlighting the critical need for responsiveness and intuitive design. Timely, clear, and noticeable feedback for both correct and incorrect actions and simple and intuitive interaction patterns [54] could be key strategies to emphasize usability for the elderly within MR. Additionally, the improvement of hand and finger tracking within the display can aid in precise control, making these technologies more accessible and enjoyable for older users.

The optimization of device tracking to improve timing accuracy and the incorporation of seating options [79] aims to mitigate physical discomforts, such as back pain, which are significant barriers to technology adoption among the elderly. This approach underscores the importance of simplifying MR device operation and tailoring content to accommodate the diverse needs and capabilities of the older population [27]. To achieve this, we recommend a holistic approach to MR device enhancement, focusing on the integration of customizable physical features, such as interchangeable lenses, and the development of a user-friendly interface that incorporates multimodal feedback mechanisms. These could include tactile feedback modalities for timing and button operation, or visual and acoustic modalities [52] for error correction and motivational cues [1].

Furthermore, addressing ergonomic concerns through general device weight, improved field of view, and simplified head attachment mechanisms is essential for reducing posture-related discomforts and enhancing the overall user experience [68]. These recommendations aim to foster a more inclusive, accessible, and enjoyable MR environment for the elderly, potentially expanding their engagement with modern technologies and enriching their lives through new, immersive experiences.

7.2 Limitations and Future Work

Our findings are limited by the provision of a relatively small sample size, which could restrict the generalizability of the findings. Additionally, only initial contact and brief interaction with the devices were observed, while participants noted that an adjustment period is required and a training effect occurs. Long-term observation would be desirable to examine the actual usage behavior of the devices. By means of a follow-up, it could be investigated what potential design spaces in addressing MR for the elderly exist in a user-centered approach [41], paired with an open session on possible applications of MR.

8 CONCLUSION

This study explored the physical and mental barriers affecting elderly engagement with MR technologies and identified facilitators for their use. Key factors impacting older adults' MR device engagement include emotional response, ergonomics and handling, usability, learning competence, and acceptance. Age-related perceptions of technology exclusion and challenges in user interface responsiveness present significant barriers. However, interest remains high among the elderly for MR applications that cater to their interests and capabilities. Recommendations for improving MR technology for older users involve simplifying interfaces, accommodating slower response times, and using multimodal feedback to enhance usability and comfort. These adjustments could make MR more enriching and accessible for older adults, suggesting a need for further research to refine MR for this demographic. While the current cohort of elderly individuals faces specific challenges, future generations might experience changes in their interaction with MR technologies, which could affect the durability of these findings. As MR technology continues to evolve, and subsequent generations are likely to be more familiar with digital devices, aspects related to usability and learning competence might become less significant. Nevertheless, the mentioned recommendations for improving MR technology interfaces, responsiveness, and multimodality will likely remain relevant. Ongoing research is necessary to ensure that MR technologies continue to meet the needs and provide benefits across different generations of elderly users.

ACKNOWLEDGMENTS

This research was funded by the Hessian Ministry for Science and Art, Germany (FL1, Mittelbau). We thank Barbara Klein and Diana Völz for their support of our research.

REFERENCES

[1] Vero Vanden Abeele, Brenda Schraepen, Hanne Huygelier, Celine Gillebert, Kathrin Gerling, and Raymond Van Ee. 2021. Immersive Virtual Reality for Older Adults: Empirically Grounded Design Guidelines. *ACM Trans. Access. Comput.* 14, 3, Article 14 (aug 2021), 30 pages. https://doi.org/10.1145/3470743

[2] Imtiaz Arafat, Sharif Mohammad Shahnewaz Ferdous, and John Quarles. 2018. Cybersickness-Provoking Virtual Reality Alters Brain Signals of Persons with Multiple Sclerosis. 1–120. https://doi.org/10.1109/VR.2018.8446194

[3] Ashratuz Zavin Asha and Ehud Sharlin. 2023. Designing Inclusive Interaction with Autonomous Vehicles for Older Passengers. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference* (<conf-loc>, <city>Pittsburgh</city>, <state>PA</state>, <country>USA</country>, </conf-loc>) *(DIS '23)*. Association for Computing Machinery, New York, NY, USA, 2138–2154. https://doi.org/10.1145/3563657.3596045

[4] Aaron Bangor, Philip T Kortum, and James T Miller. 2008. An empirical evaluation of the system usability scale. *Intl. Journal of Human–Computer Interaction* 24, 6 (2008), 574–594.

[5] Diana Barsasella, Shankari Priya Chakkaravarthi, Hee-Jung Chung, Mina Hur, Shabbir Syed Abdul, Shwetambara Malwade, Chia-Chi Chang, Megan F. Liu, and Yu-Chuan Li. 2020. Acceptability of Virtual Reality among Older People: Ordinal Logistic Regression Study from Taiwan. In *Proceedings of the 6th International Conference on Bioinformatics Research and Applications* (Seoul, Republic of Korea) *(ICBRA '19)*. Association for Computing Machinery, New York, NY, USA, 145–151. https://doi.org/10.1145/3383783.3383804

[6] John V Basmajian. 1988. Research foundations of EMG biofeedback in rehabilitation. *Biofeedback and Self-regulation* 13, 4 (1988), 275–298.

[7] Rosa M. Baños, Ernestina Etchemendy, Diana Castilla, Azucena García-Palacios, Soledad Quero, and Cristina Botella. 2012. Positive mood induction procedures for virtual environments designed for elderly people. *Interacting with Computers* 24, 3 (April 2012), 131–138. https://doi.org/10.1016/j.intcom.2012.04.002 arXiv:https://academic.oup.com/iwc/article-pdf/24/3/131/2026292/iwc24-0131.pdf

[8] Steve Benford and Gabriella Giannachi. 2011. *Performing mixed reality.* Mit Press.

[9] Kristina Berntsen, Ricardo Colomo Palacios, and Eduardo Herranz. 2016. Virtual Reality and Its Uses: A Systematic Literature Review. In *Proceedings of the Fourth International Conference on Technological Ecosystems for Enhancing Multiculturality* (Salamanca, Spain) *(TEEM '16)*. Association for Computing Machinery, New York, NY, USA, 435–439. https://doi.org/10.1145/3012430.3012553

[10] Pradipta Biswas, Pilar Orero, Manohar Swaminathan, Kavita Krishnaswamy, and Peter Robinson. 2021. Adaptive Accessible AR/VR Systems. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI EA '21)*. Association for Computing Machinery, New York, NY, USA, Article 92, 7 pages. https://doi.org/10.1145/3411763.3441324

[11] Jonas Blattgerste, Patrick Renner, and Thies Pfeiffer. 2019. Augmented Reality Action Assistance and Learning for Cognitively Impaired People: A Systematic Literature Review. In *Proceedings of the 12th ACM International Conference on PErvasive Technologies Related to Assistive Environments* (Rhodes, Greece) *(PETRA '19)*. Association for Computing Machinery, New York, NY, USA, 270–279. https://doi.org/10.1145/3316782.3316789

[12] Louanne Boyd, Kendra Day, Natalia Stewart, Kaitlyn Abdo, kathleen lamkin, and Erik Linstead. 2018. Leveling the Playing Field: Supporting Neurodiversity Via Virtual Realities. *Technology & Innovation* 20 (11 2018). https://doi.org/10.21300/20.1-2.2018.105

[13] Kilian Brachtendorf, Benjamin Weyers, and Daniel Zielasko. 2020. Towards Accessibility in VR-Development of an Affordable Motion Platform for Wheelchairs. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. IEEE, 291–292.

[14] Arthur Theil Cabreira and Faustina Hwang. 2016. How Do Novice Older Users Evaluate and Perform Mid-Air Gesture Interaction for the First Time?. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction* (Gothenburg, Sweden) *(NordiCHI '16)*. Association for Computing Machinery, New York, NY, USA, Article 122, 6 pages. https://doi.org/10.1145/2971485.2996757

[15] Arthur Theil Cabreira and Faustina Hwang. 2018. Text or image? investigating the effects of instruction type on mid-air gesture making with novice older adults. In *Proceedings of the 10th Nordic Conference on Human-Computer Interaction* (Oslo, Norway) *(NordiCHI '18)*. Association for Computing Machinery, New York, NY, USA, 452–459. https://doi.org/10.1145/3240167.3240222

[16] M.S. Cameirão, S.B.i. Badia, E.D. Oller, et al. 2010. Neurorehabilitation using the virtual reality based Rehabilitation Gaming System: methodology, design, psychometrics, usability and validation. *Journal of NeuroEngineering and Rehabilitation* 7 (2010), 48. https://doi.org/10.1186/1743-0003-7-48

[17] Long Chen, Thomas W Day, Wen Tang, and Nigel W John. 2017. Recent Developments and Future Challenges in Medical Mixed Reality. In *2017 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. 123–135. https://doi.org/10.1109/ISMAR.2017.29

[18] Weiqin Chen. 2021. Towards Personalized XR Training and Rehabilitation Applications for Older adults. In *Proceedings of the 9th International Conference on Software Development and Technologies for Enhancing Accessibility and Fighting Info-Exclusion* (Online, Portugal) *(DSAI '20)*. Association for Computing Machinery, New York, NY, USA, 163–167. https://doi.org/10.1145/3439231.3439271

[19] Adrian David Cheok, Keng Soon Teh, Ta Huynh Duy Nguyen, Tran Cong Thien Qui, Shang Ping Lee, Wei Liu, Cheng Cchen Li, Diego Diaz, and Clara Boj. 2006. Social and Physical Interactive Paradigms for Mixed-Reality Entertainment. *Comput. Entertain.* 4, 2 (apr 2006), 5–es. https://doi.org/10.1145/1129006.1129015

[20] Alice Chirico, Pietro Cipresso, David B Yaden, Federica Biassoni, Giuseppe Riva, and Andrea Gaggioli. 2017. Effectiveness of immersive videos in inducing awe: an experimental study. *Scientific reports* 7, 1 (2017), 1218.

[21] Yujin Choi and Yoon Sang Kim. 2022. An Adaptive UI Based on User-Satisfaction Prediction in Mixed Reality. *Applied Sciences* 12, 9 (2022). https://doi.org/10.3390/app12094559

[22] Ana-Isabel Corregidor-Sánchez, Antonio Segura-Fragoso, Juan-José Criado-Álvarez, Marta Rodríguez-Hernández, Alicia Mohedano-Moriano, and Begoña Polonio-López. 2020. Effectiveness of Virtual Reality Systems to Improve the Activities of Daily Life in Older People. *International Journal of Environmental Research and Public Health* 17, 17 (2020). https://doi.org/10.3390/ijerph17176283

[23] Sara J Czaja and Chin Chin Lee. 2007. The impact of aging on access to technology. *Universal Access in the Information Society* 5, 4 (2007), 341–349.

[24] Nathan D'Cunha, Dung Nguyen, Nenad Naumovski, Andrew Mckune, Jane Kellett, Ekavi Georgousopoulou, Jane Frost, and Stephen Isbel. 2019. A Mini-Review of Virtual Reality-Based Interventions to Promote Well-Being for People Living with Dementia and Mild Cognitive Impairment. *Gerontology* 65 (05 2019), 430–440. https://doi.org/10.1159/000500040

[25] Eling D de Bruin, D Schoene, G Pichierri, and Stuart T Smith. 2010. Use of virtual reality technique for the training of motor control in the elderly. *Zeitschrift für Gerontologie und Geriatrie* 43, 4 (2010), 229–234.

[26] Julia Diemer, Georg W. Alpers, Henrik M. Peperkorn, Youssef Shiban, and Andreas Mühlberger. 2015. The impact of perception and presence on emotional reactions: a review of research in virtual reality. *Frontiers in Psychology* 6 (2015). https://doi.org/10.3389/fpsyg.2015.00026

[27] John Dudley, Lulu Yin, Vanja Garaj, and Per Ola Kristensson. 2023. Inclusive Immersion: a review of efforts to improve accessibility in virtual reality, augmented reality and the metaverse. *Virtual Real.* 27, 4 (sep 2023), 2989–3020. https://doi.org/10.1007/s10055-023-00850-8

[28] Matt Dunleavy and Chris Dede. 2014. Augmented reality teaching and learning. *Handbook of research on educational communications and technology* (2014), 735–745.

[29] Elizabeth FitzGerald, Rebecca Ferguson, Anne Adams, Mark Gaved, Yishay Mor, and Rhodri Thomas. 2013. Augmented reality and mobile learning: the state of the art. *International Journal of Mobile and Blended Learning (IJMBL)* 5, 4 (2013), 43–58.

[30] Yu Fu, Yan Hu, and Veronica Sundstedt. 2022. A Systematic Literature Review of Virtual, Augmented, and Mixed Reality Game Applications in Healthcare. *ACM Trans. Comput. Healthcare* 3, 2, Article 22 (mar 2022), 27 pages. https://doi.org/10.1145/3472303

[31] Luciano Gamberini, Mariano Alcaniz, Giuseppe Barresi, Marcos Fabregat, Francisco Ibanez, and Laura Prontu. 2006. Cognition, technology and games for the elderly: An introduction to ELDERGAMES Project. *PsychNology Journal* 4, 3 (2006), 285–308.

[32] R.I. García-Betances, V. Jiménez-Mixco, M.T. Arredondo, and M.F. Cabrera-Umpiérrez. 2015. Using Virtual Reality for Cognitive Training of the Elderly. *American Journal of Alzheimer's Disease and Other Dementias* 30, 1 (2015), 49–54. https://doi.org/10.1177/1533317514545866

[33] Kathrin Gerling and Katta Spiel. 2021. A Critical Examination of Virtual Reality Technology in the Context of the Minority Body. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 599, 14 pages. https://doi.org/10.1145/3411764.3445196

[34] Evgenia Gkini, Ioannis Voyiatzis, and C. Sgouropoulou. 2021. Head-Mounted Display Systems as Visual Aids for the Visually Impaired:A Survey. 323–327. https://doi.org/10.1145/3503823.3503883

[35] Laura Götz, Radiah Rivu, Florian Alt, Albrecht Schmidt, and Ville Mäkelä. 2022. Real-World Methods of Autobiographical Recall in Virtual Reality. In *Nordic Human-Computer Interaction Conference* (Aarhus, Denmark) *(NordiCHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 31, 11 pages. https://doi.org/10.1145/3546155.3546704

[36] Peter Gregor, Alan F. Newell, and Mary Zajicek. 2002. Designing for dynamic diversity: interfaces for older people. In *Proceedings of the Fifth International ACM Conference on Assistive Technologies* (Edinburgh, Scotland) *(Assets '02)*. Association for Computing Machinery, New York, NY, USA, 151–156. https://doi.org/10.1145/638249.638277

[37] Rongkai Guo, Gayani Samaraweera, and John Quarles. 2013. The effects of VEs on mobility impaired users: presence, gait, and physiological response. In *Proceedings of the 19th ACM Symposium on Virtual Reality Software and Technology* (Singapore) *(VRST '13)*. Association for Computing Machinery, New York, NY, USA, 59–68. https://doi.org/10.1145/2503713.2503719

[38] Rongkai Guo, Gayani Samaraweera, and John Quarles. 2015. Mobility impaired users respond differently than healthy users in virtual environments. *Comput. Animat. Virtual Worlds* 26, 5 (sep 2015), 509–526. https://doi.org/10.1002/cav.1610

[39] ZY. Hoe, IJ. Lee, CH. Chen, et al. 2019. Using an augmented reality-based training system to promote spatial visualization ability for the elderly. *Universal Access in the Information Society* 18 (2019), 327–342. https://doi.org/10.1007/s10209-017-0597-x

[40] Gregory Hough, Ian Williams, and Cham Athwal. 2014. Measurements of live actor motion in mixed reality interaction. In *2014 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. 99–104. https://doi.org/10.1109/ISMAR.2014.6948414

[41] Iolanda Iacono and Patrizia Marti. 2014. Engaging older people with participatory design. In *Proceedings of the 8th Nordic Conference on Human-Computer Interaction: Fun, Fast, Foundational* (Helsinki, Finland) *(NordiCHI '14)*. Association for Computing Machinery, New York, NY, USA, 859–864. https://doi.org/10.1145/2639189.2670180

[42] MY. Jeng, FY. Pai, and TM. Yeh. 2017. The Virtual Reality Leisure Activities Experience on Elderly People. *Applied Research Quality Life* 12 (2017), 49–65. https://doi.org/10.1007/s11482-016-9452-0

[43] Brooke John. 1996. SUS: a" quick and dirty" usability scale. *Usability evaluation in industry* (1996), 189–194.

[44] Marta Kersten-Oertel, Pierre Jannin, and D. Louis Collins. 2012. DVV: A Taxonomy for Mixed Reality Visualization in Image Guided Surgery. *IEEE Transactions on Visualization and Computer Graphics* 18, 2 (feb 2012), 332–352. https://doi.org/10.1109/TVCG.2011.50

[45] Oliver Korn, Lea Buchweitz, Adrian Rees, Gerald Bieber, Christian Werner, and Klaus Hauer. 2018. Using Augmented Reality and Gamification to Empower Rehabilitation Activities and Elderly Persons. A Study Applying Design Thinking *(AHFE 2018: Advances in Artificial Intelligence, Software and Systems Engineering, Vol. 787)*. Springer, Cham, 219 – 229. https://doi.org/10.1007/978-3-319-94229-2_21

[46] Chiara Leonardi, Adriano Albertini, Fabio Pianesi, and Massimo Zancanaro. 2010. An exploratory study of a touch-based gestural interface for elderly. In *Proceedings of the 6th Nordic Conference on Human-Computer Interaction: Extending Boundaries* (Reykjavik, Iceland) *(NordiCHI '10)*. Association for Computing Machinery, New York, NY, USA, 845–850. https://doi.org/10.1145/1868914.1869045

[47] H. Lim, D. Hooshyar, H. Ji, et al. 2019. SmartSenior: Automatic Content Personalization Through Semi-supervised Learning. *Wireless Personal Communications* 105 (2019), 461–473. https://doi.org/10.1007/s11277-018-5947-3

[48] Lizheng Liu, Jianjun Cui, Jian Niu, Na Duan, Xianjia Yu, Qingqing Li, Shih-Ching Yeh, and Li-Rong Zheng. 2020. Design of Mirror Therapy System Base on Multi-Channel Surface-Electromyography Signal Pattern Recognition and Mobile Augmented Reality. *Electronics* 9, 12 (2020). https://doi.org/10.3390/electronics9122142

[49] Q Liu, Y Wang, Q Tang, and Z Liu. 2020. Do You Feel the Same as I Do? Differences in Virtual Reality Technology Experience and Acceptance Between Elderly Adults and College Students. *Frontiers in Psychology* 11 (25 Sep 2020), 573673. https://doi.org/10.3389/fpsyg.2020.573673

[50] A. Lopez-Martinez, S. Santiago-Ramajo, A. Caracuel, C. Valls-Serrano, M. J. Hornos, and M. J. Rodriguez-Fortiz. 2011. Game of gifts purchase: Computer-based training of executive functions for the elderly. In *Proceedings of IEEE 1st Int. Conf. on Serious Games and Applications for Health (SeGAH)*. 1–8.

[51] M. Rasel Mahmud, Alberto Cordova, and John Quarles. 2023. The Eyes Have It: Visual Feedback Methods to Make Walking in Immersive Virtual Reality More Accessible for People With Mobility Impairments While Utilizing Head-Mounted Displays. In *Proceedings of the 25th International ACM SIGACCESS Conference on Computers and Accessibility* (, New York, NY, USA,) *(ASSETS '23)*. Association for Computing Machinery, New York, NY, USA, Article 36, 10 pages. https://doi.org/10.1145/3597638.3608406

[52] M. Rasel Mahmud, Alberto Cordova, and John Quarles. 2023. The Eyes Have It: Visual Feedback Methods to Make Walking in Immersive Virtual Reality More Accessible for People With Mobility Impairments While Utilizing Head-Mounted Displays. In *Proceedings of the 25th International ACM SIGACCESS Conference on Computers and Accessibility* (, New York, NY, USA,) *(ASSETS '23)*. Association for Computing Machinery, New York, NY, USA, Article 36, 10 pages. https://doi.org/10.1145/3597638.3608406

[53] Steve Mann, Tom Furness, Yu Yuan, Jay Iorio, and Zixin Wang. 2018. All Reality: Virtual, Augmented, Mixed (X), Mediated (X, Y), and Multimediated Reality. *Presence: Teleoperators and Virtual Environments* 11, 4 (2018), 425–434.

[54] A. L. Morán, C. Ramírez-Fernández, V. Meza-Kubo, et al. 2015. On the Effect of Previous Technological Experience on the Usability of a Virtual Rehabilitation Tool for the Physical Activation and Cognitive Stimulation of Elders. *Journal of Medical Systems* 39, 104 (2015). https://doi.org/10.1007/s10916-015-0297-0

[55] Rana Mostaghel and Pejvak Oghazi. 2017. Elderly and technology tools: a fuzzy-set qualitative comparative analysis. *Quality & Quantity* 51 (2017), 1969–1982. https://doi.org/10.1007/s11135-016-0390-6

[56] Martez Mott, John Tang, Shaun Kane, Edward Cutrell, and Meredith Ringel Morris. 2020. "I just went into it assuming that I wouldn't be able to have the full experience": Understanding the Accessibility of Virtual Reality for People with Limited Mobility. In *Proceedings of the 22nd International ACM SIGACCESS Conference on Computers and Accessibility* (, Virtual Event, Greece,) *(ASSETS '20)*. Association for Computing Machinery, New York, NY, USA, Article 43, 13 pages. https://doi.org/10.1145/3373625.3416998

[57] Vivian Genaro Motti. 2019. Designing emerging technologies for and with neurodiverse users. In *Proceedings of the 37th ACM International Conference on the Design of Communication* (Portland, Oregon) *(SIGDOC '19)*. Association for Computing Machinery, New York, NY, USA, Article 11, 10 pages. https://doi.org/10.1145/3328020.3353946

[58] Sarah Nichols. 1999. Physical ergonomics of virtual environment use. *Applied Ergonomics* 30, 1 (1999), 79–90. https://doi.org/10.1016/S0003-6870(98)00045-3

[59] Ifeanyi Paul Odenigbo, Alaa AlSlaity, and Rita Orji. 2022. Augmented and Virtual Reality-Driven Interventions for Healthy Behavior Change: A Systematic Review. In *ACM International Conference on Interactive Media Experiences* (Aveiro, JB, Portugal) *(IMX '22)*. Association for Computing Machinery, New York, NY, USA, 53–68. https://doi.org/10.1145/3505284.3529964

[60] M Perkins and J Roe. 2024. Academic publisher guidelines on AI usage: A ChatGPT supported thematic analysis. *F1000Research* 12 (2024), 1398. https://doi.org/10.12688/f1000research.142411.2 Version 2; peer review: 3 approved, 1 approved with reservations.

[61] Johanna Pirker, Andreas Dengel, Michael Holly, and Saeed Safikhani. 2020. Virtual Reality in Computer Science Education: A Systematic Review. In *26th ACM Symposium on Virtual Reality Software and Technology* (Virtual Event, Canada) *(VRST '20)*. Association for Computing Machinery, New York, NY, USA, Article 8, 8 pages. https://doi.org/10.1145/3385956.3418947

[62] Holger Regenbrecht and Thomas Schubert. 2002. Real and illusory interactions enhance presence in virtual environments. *Presence: Teleoperators and Virtual Environments* 11, 4 (2002), 425–434.

[63] Giuseppe Riva and John A. Waterworth. 2014. Being Present in a Virtual World. In *The Oxford Handbook of Virtuality*. Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199826162.013.015 arXiv:https://academic.oup.com/book/0/chapter/212314091/chapter-ag-pdf/44594064/book_28128_section_212314091.ag.pdf

[64] Belén Rubio Ballester, Sergi Bermúdez i Badia, and Paul F. M. J. Verschure. 2012. Including Social Interaction in Stroke VR-Based Motor Rehabilitation Enhances Performance: A Pilot Study. *Presence: Teleoperators and Virtual Environments* 21, 4 (11 2012), 490–501. https://doi.org/10.1162/PRES_a_00129 arXiv:https://direct.mit.edu/pvar/article-pdf/21/4/490/1625295/pres_a_00129.pdf

[65] Rômulo Santos Silva, Artur Martins Mol, and Lucila Ishitani. 2019. Virtual reality for older users: a systematic literature review. *International Journal of Virtual Reality* 19, 1 (Jan. 2019), 11–25. https://doi.org/10.20870/IJVR.2019.19.1.2908

[66] Tanja Schroeder, Laura Dodds, Andrew Georgiou, Heiko Gewald, and Joyce Siette. 2023. Older Adults and New Technology: Mapping Review of the Factors Associated With Older Adults' Intention to Adopt Digital Technologies. *JMIR Aging* 6 (16 May 2023), e44564. https://doi.org/10.2196/44564

[67] Nicu Sebe, Michael S Lew, and Thomas S Huang. 2004. The state-of-the-art in human-computer interaction. In *International Workshop on Computer Vision in Human-Computer Interaction*. Springer, 1–6.

[68] Jessica Sehrt, Henrico Putra Neumann, Julian Niclas Wenzel, Luca Kindermann, and Valentin Schwind. 2022. The Negative Effect on Postural Ergonomics of Non-Sedentary Workplace Desks in Virtual Reality. In *Proceedings of Mensch Und Computer 2022* (Darmstadt, Germany) *(MuC '22)*. Association for Computing Machinery, New York, NY, USA, 365–370. https://doi.org/10.1145/3543758.3547541

[69] Alexa F. Siu, Mike Sinclair, Robert Kovacs, Eyal Ofek, Christian Holz, and Edward Cutrell. 2020. Virtual Reality Without Vision: A Haptic and Auditory White Cane to Navigate Complex Virtual Worlds. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376353

[70] Maximilian Speicher, Brian D. Hall, and Michael Nebeling. 2019. What is Mixed Reality?. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3290605.3300767

[71] Shabbir Syed-Abdul, Shweta Malwade, Agung Ayu Nursetyo, et al. 2019. Virtual reality among the elderly: a usefulness and acceptance study from Taiwan. *BMC Geriatrics* 19, 1 (2019), 223. https://doi.org/10.1186/s12877-019-1218-8

[72] Mauro Teófilo, Vicente Lucena Jr, Josiane Nascimento, Taynah Miyagawa, and Fran Maciel. 2018. Evaluating accessibility features designed for virtual reality context. 1–6. https://doi.org/10.1109/ICCE.2018.8326167

[73] Kong Saoane Thach, Reeva Lederman, and Jenny Waycott. 2021. How older adults respond to the use of Virtual Reality for enrichment: a systematic review. In *Proceedings of the 32nd Australian Conference on Human-Computer Interaction* (Sydney, NSW, Australia) *(OzCHI '20)*. Association for Computing Machinery, New York, NY, USA, 303–313. https://doi.org/10.1145/3441000.3441003

[74] Kong Saoane Thach, Reeva Lederman, and Jenny Waycott. 2021. How Older Adults Respond to the Use of Virtual Reality for Enrichment: A Systematic Review. In *Proceedings of the 32nd Australian Conference on Human-Computer Interaction* (Sydney, NSW, Australia) *(OzCHI '20)*. Association for Computing Machinery, New York, NY, USA, 303–313. https://doi.org/10.1145/3441000.3441003

[75] A. Vasconcelos, P. A. Silva, J. Caseiro, F. Nunes, and L. F. Teixeira. 2012. Designing tablet-based games for seniors: The example of cogniplay, a cognitive gaming platform. In *Proceedings of the 4th Int. Conf. on Fun and Games (FnG '12)*. ACM, New York, NY, USA, 1–10.

[76] Thomas J. Williams, Simon L. Jones, Christof Lutteroth, Elies Dekoninck, and Hazel C Boyd. 2021. Augmented Reality and Older Adults: A Comparison of Prompting Types. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (<conf-loc>, <city>Yokohama</city>, <country>Japan</country>, </conf-loc>) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 723, 13 pages. https://doi.org/10.1145/3411764.3445476

[77] He Zhang, Chuhao Wu, Jingyi Xie, Yao Lyu, Jie Cai, and John M. Carroll. 2023. Redefining Qualitative Analysis in the AI Era: Utilizing ChatGPT for Efficient Thematic Analysis. arXiv:2309.10771 [cs.HC]

[78] Yuhang Zhao, Edward Cutrell, Christian Holz, Meredith Ringel Morris, Eyal Ofek, and Andrew D. Wilson. 2019. SeeingVR: A Set of Tools to Make Virtual Reality More Accessible to People with Low Vision. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3290605.3300341

[79] Daniel Zielasko and Bernhard E. Riecke. 2020. Sitting vs. Standing in VR: Towards a Systematic Classification of Challenges and (Dis)Advantages. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. 297–298. https://doi.org/10.1109/VRW50115.2020.00067