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HoloMoves
CREATING HEALTHY RECOVERY

Optical See-Through vs. Video See-Through Mixed Reality for Rehabilitation

Exploring the effects of mixed reality on the experience of motor rehabilitation of ABI patients through the eyes of the patient and therapist.

Master Thesis Interaction Technology

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Abstract

There is an increasing interest in technology-based interventions for acquired brain injury (ABI) patients, such as with X Reality (XR). Several studies suggest greater improvements in motor function after rehabilitation with the use of XR training. However, these studies rarely provide motivation for their selected use of XR technology even though their characteristics differ greatly. This is especially seen in mixed reality (MR) where optical see-through and video see-through are optional methods, but little is known of how their effect on rehabilitation differs. Understanding how these different technologies influence the experience of ABI patients and their therapists during rehabilitation can help increase the quality of rehabilitation with the use of MR. Because of this, the primary goal of this thesis was to explore how the differentiating features of optical see-through (Microsoft HoloLens 2) and video see-through (Meta Quest Pro) differently affect the experience of motor rehabilitation of ABI patients from the perspective of the patient and the therapist.

This thesis consisted of four stages: (1) the context exploration through semi-structured interviews to get a better understanding of the current rehabilitation experience of ABI patients and their therapists, (2) investigating the differentiating features of the two MR headsets through the Design exploration tests with healthy participants to get a better grasp of the technical specifications and explore the potential design possibilities, (3) creating game designs for upper limb motor rehabilitation that allow to test how the differentiating features influence the experience of ABI patients, and (4) actually testing with ABI patients and their therapist using a convergent mixed methods research design approach to explore how these differentiating features affect their experience.

The Design exploration tests (stage 2) showed significant differences in regard to the spatial awareness of participants caused by the different Field of View (FoV) size which indicated that participants had a harder time finding the next virtual objects and had less of an overview with a smaller FoV. Furthermore, the tests showed that people would move slower and more careful with a smaller FoV even though they did not experience it as such. Both these findings were also confirmed by the ABI experience test (stage 4) where patients experienced a harder time finding objects with the smaller FoV of the HoloLens 2. However, instead of moving slower they would show more frantic search behavior with a smaller FoV. This could most likely be explained by the difference in posture, participants in stage 2 were walking while participants in stage 4 were seated. However, this influence of MR systems and the postures of participants while using the MR systems on the behavior could have important implications for rehabilitation where movements of patients are of importance for recovery. This is especially important as ABI patients argued they would be open to using MR for rehabilitation as long as it benefitted their recovery. Another difference found between the healthy participants of stage 2 and the ABI patients of stage 4 was their experience with the image quality of the Quest Pro. Healthy participants argued the image quality of the real world was grainy and of poor quality, however, the ABI patients did not notice this. This can again likely be explained by the fact that the ABI patients were seated and did not have to look much at the background, while the healthy participants had to walk around and pay attention to their surroundings. In addition, it is likely that ABI patients experience more indifference resulting in less outspoken answers in general. Overall, my thesis showed that the individual features of MR systems do play a role in the experience of users during rehabilitation and should be considered and motivated in future research.

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1. Introduction

It is estimated that yearly 130.000 people in the Netherlands suffer from a form of acquired brain injury (ABI) which results in a total of approximately 650.000 people who suffer from the effects of ABI (Hersenletsel uitleg, n.d.; Zorg Voor Beter, 2022). ABI is an umbrella term for brain damage received at some point in one's life after birth including traumatic brain injury (TBI), cerebral vascular accident (CVA) or stroke, aneurysm, brain tumor, and vestibular dysfunction (Ciuffreda & Kapoor, 2012); where stroke is the most occurring.

The effects of an ABI can be both mental and physical, however, they differ for every person and can range from mild to profound (BetterHealth, 2014; Ciuffreda & Kapoor, 2012; Gresham et al., 1995; Joubran et al., 2022). About 70-85% of first strokes are accompanied by hemiparesis which can lead to gait dysfunction which greatly affects the independence and quality of life of a person (Langhorne et al., 2011; Weishaupt & Sachdev, 2021; Wilson et al., 2019). A common complaint from stroke patients is that they still cannot walk safely and efficiently 6 months after the stroke occurred (Dobkin, 2004; Lord et al., 2004). Similarly, Dobkin (2004) stated that people with ambulatory hemiparesis have four times the risk of falls and ten times the risk of hip fractures of healthy people (Dobkin, 2004). Similarly, activities of daily life (ADL) can be affected due to hemiparesis, meaning that stroke patients often need help with tasks such as dressing oneself, eating, grabbing things, and walking (Weishaupt & Sachdev, 2021). Upper- and lower limb motor rehabilitation are therefore important forms of rehabilitation for people who are affected by an ABI (Wilson et al., 2019).

The period of recovery following an ABI varies and is not always complete, however, rehabilitation is important to help recovery (Ciuffreda & Kapoor, 2012; Wilson et al., 2019). Rehabilitation is a restorative and learning process which aims to expedite and maximize recovery from ABI, the goal is for the patient to regain freedom of movement and functional independence (Gresham et al., 1995). Currently this is done through exercises practiced with a physical therapist, these exercises can include standing on one leg or with eyes closed, wobble board exercises, using a treadmill, with the use of an obstacle course, grabbing objects, precise finger movement, or general training of ADL skills (Papegaaij et al., 2017). Additionally, there is an increasing interest in technology-based interventions for both mild-moderate ABI patients and severe ABI patients, such as with the use of augmented reality (AR), virtual reality (VR), or mixed reality (MR) (Papegaaij et al., 2017; Wilson et al., 2019).

AR, MR, and VR are described in a number of ways, even so, AR generally refers to laying digital information over the real world that is present in real-time, MR aims to merge the physical world with virtual information, while VR refers to a system that occludes information from the environment while presenting a virtual environment to the user (Milgram et al., 1995; Rauschnabel et al., 2022). XR is often used as the umbrella term of AR, MR, and VR, and can be the acronym for either eXtended Reality or X Reality, the latter being employed in this research. XR has a few traits that can be beneficial to the rehabilitation of ABI patients. It can create immersive and enriching environments which can increase the motivation of the patients and promote rehabilitation (Laver et al., 2011). In addition, it can create a safe environment for training ADL, think of an exercise in a kitchen setting which could otherwise be dangerous to train because of sharp or hot objects (Colomer et al., 2016). Lastly, Iruthayarajah et al. (2017) performed a meta-analysis and found that throughout literature, XR interventions stimulates the recovery of impaired balance in stroke patients more effectively compared to traditional interventions (Iruthayarajah et al., 2017).

HoloMoves is a company that uses MR to promote rehabilitation of patients in rehabilitation centers, hospitals, and other healthcare facilities (HoloMoves, n.d.; Valkenet et al., 2021). They do this by providing patients with movement games to be more physically active to prevent unnecessary deterioration of physical condition, and by providing patients with engaging education modules to support them in making healthy choices and undertaking physical activity (HoloMoves, n.d.). At this point there are products for several patient groups, such as those with spinal cord injuries, cardiology, pulmonary, and oncology diseases, and for those after a heart surgery. In addition, they are working on new products focused on the motor rehabilitation of ABI patients, with the focus on CVA patients.

Currently HoloMoves uses the Microsoft HoloLens 2 glasses in their products, these glasses offer optical see-through mixed reality, meaning, the real world is visible through the glasses with an additional layer of 3D digital information that is spatially placed in a room (Microsoft, n.d.; Orban & Perey, 2021). Another form of mixed reality is through a video see-through device where a video of the real world is shown in real time with additional virtual content merged in. Meta released a new headset in 2022 called the Meta Quest Pro which uses this video see-through technology (Meta Quest, 2022; Orban & Perey, 2021). These different forms of mixed reality also have unique characteristics that might influence the user experience, especially when used in motor rehabilitation of ABI patients. However, as Butz et al. (2022) argue, there is currently little known about the motivation for the use of AR/VR/MR technologies and their specification when used during medical rehabilitation (Butz et al., 2022). By understanding how different qualities of mixed reality systems might affect the experience of stroke patients and their therapist might help increase the quality of rehabilitation.

To do this, I'll first dive deeper into what different forms of XR entail, how the different forms of MR differ from each other, and how XR is currently applied in rehabilitation. Secondly, to get a better image of the technology that I'll be working with and where the design opportunities might lay, a study on the technological specifications and the differences between the MR systems will be done. From this a game will be designed that will allow to test how their differentiating features might influence the experience of users. Last, a study on how ABI patients and their therapists experience this game, and the different forms of MR will be done.

2. Background

The literature study is part of a previous project written by me for the course Research Topics which was done prior to starting my thesis. The chapter has since been altered to fit the use of this thesis.

2.1 X Reality

Defining the terms Augmented Reality (AR), Virtual reality (VR) and Mixed reality (MR) has been the goal of researchers since the early 90s when Milgram & Kishino presented their Reality – Virtuality continuum to facilitate a better understanding of these terms and how they interconnect (Milgram & Kishino, 1994; Speicher et al., 2019). However, as Berryman (2012) pointed out, rudimentary elements of AR were already used as early as the 1940s (Berryman, 2012). Since then, the development of AR, MR, and VR has gone rapidly, especially since 2016 with an influx of reality-altering headsets which put these technologies back in the spotlight (Brigham, 2017). Because of this quick development, the discussion on the definitions and relations of the different technologies is still alive (Speicher et al., 2019). This is also seen regarding an umbrella term for these technologies of which there is also no consensus. A commonly used term is eXtended Reality (XR); however, this excludes VR because VR in definition is its own reality and not an extension of the physical world like AR and MR. Because of this, Rauschnabel et al. (2022) suggested the use of XR as an abbreviation for X Reality (XR) where the X represents a placeholder for any form of new reality, similar to an X variable in algebra. Due to its inclusive nature, this term will be used for the remainder of this research.

The following sections will discuss a commonly used XR framework proposed by Milgram & Kishinio in 1994, and why this research will instead employ the MR-centered view described by, amongst others, Rauschnabel et al. (2022). This section will be followed by describing which definitions of AR, MR and VR will be applied in this research and what types of technologies can be used to create the corresponding XR experience.

2.1.1 XR Frameworks

A number of different definitions and frameworks exist in the literature on XR. Despite the popularity of Milgram & Kishino's Reality-Virtuality continuum, there is still no clear consensus on how AR, MR, and VR should be distinguished from each other and what the term mixed reality entails (Milgram & Kishino, 1994; Speicher et al., 2019). Because it is a good basis for describing XR and its different possibilities, the Reality-Virtuality Continuum will be discussed in more detail. However, the theory is almost thirty years old and, in that time, new innovative XR technologies have entered the market and require an updated framework that create space for this. Therefore, an alternative framework, the MR-centered view, as explained by Rauschnabel et al. (2022) will be discussed, which creates space for MR to be its separate concept in contrast to Milgram & Kishino's Reality-Virtuality continuum.

The Reality-Virtuality Continuum

Milgram and Kishino were one of the first and still the most well-known to provide a taxonomy of XR in which they present their Reality-Virtuality (RV) continuum with the focus on visual displays (Milgram et al., 1995; Milgram & Kishino, 1994). To the left side of the RV continuum lies the real environment without any additional virtual information, this can be perceived directly in person or through some sort of window or display. To the right of the RV continuum lies the fully virtual environment without any additional elements of the real world. Any point on the continuum that has a mix of real and virtual information, they define as mixed reality with the sub forms being augmented reality (AR) and augmented virtuality (AV) (Milgram et al., 1995), see Figure 1.a.

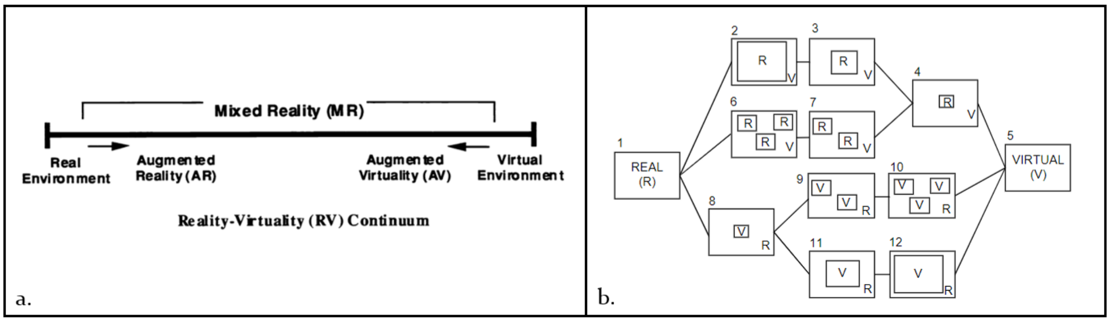


Figure 1 a. The Reality-Virtuality Continuum as presented in Milgram et al. (1995); b. Mixed Reality combination space as presented in Milgram et al. (1999).

With their continuum, Milgram et al. (1995) argue that AR and VR are in fact related to each other and with AR being on the continuum while VR is on the far-right end called virtual environment. They distinguish between AR and AV by the proportion of real vs. virtual information visually presented to the user, see Figure 1.b. (Milgram & Colquhoun, 1999). This proportion-based interpretation does present some limitations though. For example, when a user is wearing AR glasses that integrate textual information into the person's field of view, it would be considered a mixed reality environment. The relative size of the textual information in the person's field of view would determine where on the continuum it should be considered (Rauschnabel et al., 2022). This way of distinguishing systems and where they should be placed on the continuum contradict current industry practices. The continuum stems from the 90s and the technological capabilities as well as the capabilities of MR have significantly evolved (Speicher et al., 2019), therefore, other frameworks should be explored.

The MR-centered view

A different approach, called the "MR-centered view" by Rauschnabel et al. (2022), describes mixed reality as a separate concept representing its own specific type of reality that merges the real world with the virtual world. The view consists of a similar continuum as the RV-continuum, however, includes MR in the center between AR and AV (Rauschnabel et al., 2022), see Figure 2.

Hönig et al. (2015) describe MR as a space in which both physical and virtual elements are integrated, allowing for easy interaction between the two. In contrast to the RV-continuum, one space is not secondary to another, MR blurs the boundaries between environments creating one coherent space where elements from both realities can communicate in real-time (Honig et al., 2015). This enables components in one reality to react directly to what is happening in another. The rest of the MR-centered view, the AR and AV spaces, are similar to the RV-continuum. AR is a space that exists for the majority of the real environment with additional virtual information, whereas AV is for the majority a virtual space with additional real-world information. Due to the addition of MR on the continuum and the problems that are presented by classifying realities based on the virtuality/reality ratio, a different classification system is needed to distinguish realities and to understand how they relate to one another. Parveau & Adda (2018) proposed three classification criteria: immersion, interaction, and information. This method allows for a more detailed distinguishment between different technologies, especially the immersion and interaction describe where a technology would fall on the continuum and what kind of information is managed. In addition, it supports different modalities instead of only focusing on visual displays. Through the levels of immersion and interaction, the continuum can be explored to get a better understanding of the relation between AR, MR and VR.

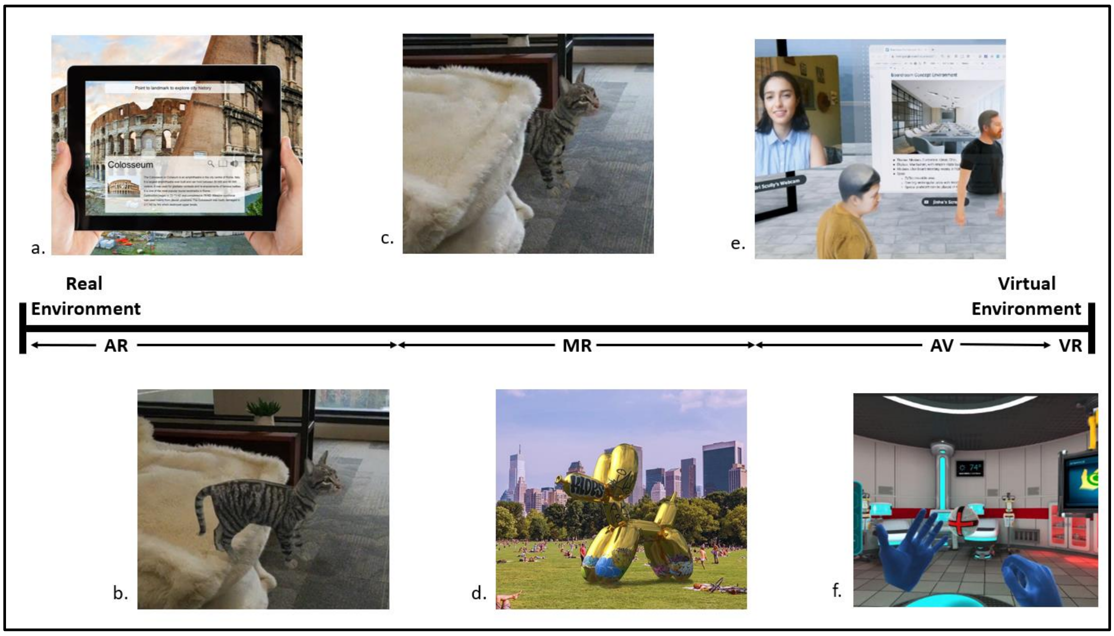


Figure 2 Representation of the MR-centered view with six examples of what the levels of immersion look like along the continuum; a. real world background with additional head stable text; b. real world background with an additional virtual cat that has no connection with the physical world; c. real world background with an additional virtual cat that is partially obscured by the real world; d. a digital representation of the real world with an additional digital real-world representation of artwork; e. a virtual background and environment with an additional real world call window; f. a virtual environment with only virtual elements.

On the far left of the continuum lays the reality without any additional virtual information. This is followed by overlaying virtual information onto the reality, entering the augmented reality space. At this first stage the information is presented to the user in a static form and can be considered head-stable (Jaekl et al., 2002). Head-stable content moves according to the orientation of the user's head and is often used when there is no relationship between virtual and real-world objects, or when it needs to get the user's attention and be processed quickly like a notification (Rauschnabel et al., 2022). There is no to limited interaction with the virtual information. Examples of this type of AR could be seen in text-based work instructions that are overlaid on the physical environment in places like construction, or in the field of tourism where tourists can see information of places of interest during a sightseeing tour (Fig 2.a.) (Han et al., 2014). To move up the continuum, more interactivity could be added to the experience. The information presented is still head-stable, however, the user can manipulate the virtual information. For example, a 3D object might be presented to the user who can turn and manipulate the object, however, the object is not related to the rest of the physical environment (Fig 2.b.). This increases the interaction without necessarily increasing the immersion (Rauschnabel et al., 2022).

The immersion can be increased by placing the virtual content anchored in a fixed position in a 3D space, meaning the content is world-stable instead of head-stable (Jaekl et al., 2002). In the case of visual augmentation, an object could be placed in a certain spot and as the user would turn away from it, they would be unable to see it and when they turn back it would still be in the same spot. This also means the user can walk around the virtual object and see it from different angles. Similarly, this can be done with auditory augmentation by anchoring certain sound augmentation to specific locations. Anchoring virtual information is often done in cases where a relationship exists between virtual information and a physical object or space, however, this is not necessary (Rauschnabel et al., 2022). When there is a relationship though, the virtual content is able to blend more with the real world by placing virtual objects on top of physical objects (e.g., a virtual vase on top of a physical table) or by having virtual objects being occluded by physical objects (Fig 2.c.) (Keil et al., 2019). At this point the user experiences greater immersion and is the experience tending toward the mixed reality space, especially when adding increased interactivity.

Interactivity can be considered as twofold in this case, virtual content interacting with the user and virtual content interacting with the real world. As previously discussed, interaction with the user entails the user being able to manipulate the virtual content, for greater immersion this should be done without a controller and instead through gesture, voice, and gaze (Parveau & Adda, 2018). Interaction with the real world comes from the spatial awareness the system has at this point of the continuum. The positioning of virtual content in the real world is already a form of interaction, when a virtual object is placed on a physical surface the objects is 'supported' by the physical surface. To take it further, kinetic interaction between virtual content and the real world can be integrated. Here the system understands how virtual content would move in the real world, think of a virtual ball that would bounce from a wall, or a virtual glass that would fall from a table and shatter on the ground. At this point the boundaries between the real and virtual world are blurred and components from both worlds can communicate in real-time (Honig et al., 2015).

Till this point of the continuum, the visual background of the XR environment has been the real world which can be done through actually seeing the real world or by having a digital representation of the real world (Azuma et al., 2001). When a digital representation of the real world is used the experience starts to move towards the space of augmented virtuality. While having the real world as digital background the added virtual content can have a clear virtual look, or the virtual content can have a digital representation of real-world objects. An example could be where the real world is shown where the user is in that moment, like a public park, with the addition of a realistic presentation of an existing artwork (Fig 2.d.). On the other hand, having a digital representation of the real world also allows for occlusion of real-world objects by overlaying those objects with virtual information, this would not be possible with optical see-through XR due to the digital information often being somewhat transparent (Rauschnabel et al., 2022). When the background of the experience is clearly a virtual environment not representing the real world anymore with real world objects present it is considered a fully augmented virtual space, an example can be a virtual meeting space with an additional window showing a real-world view of a conference call (Fig 2.e.). Last, when the entire world is a virtual world without any real-world addition it is considered virtual reality which is located on the far-right end of the continuum (Fig 2.f.).

Based on the "MR centered view" framework, definitions of AR, MR, and VR can be described. It should be noted that throughout literature these terms are used in various manners, however, for the remainder of this research the "MR centered view" will be applied as will the definitions that are given in this section. Furthermore, this section describes what kind of technology can be used to provide the corresponding XR experience.

2.1.2 Augmented Reality

Augmented reality is defined in a number of ways and can especially vary in what is included in the definition. Carmigniani et al. provide a definition that describes the general principle of AR: *Augmented Reality (AR) is a real-time direct or indirect perception of a physical real-world environment that has been enhanced or augmented by adding virtual computer-generated information to it* (Carmigniani et al., 2011). The goal of AR is to add digital information as an overlay to the real world to enhance the experience and understanding of a user in a certain context (Berryman, 2012). In other words, AR aims to enhance the user's perception of, and interaction with the real world, which can be done through several modalities like sight, hearing, touch, and smell (Azuma et al., 2001; Carmigniani et al., 2011). While the focus is often on the sense of sight with additional auditory information, other modalities can also be the main modality. Furthermore, due to the nature AR, users can both interact with real-world objects and virtual objects which also allows for natural haptic feedback of the real world, or by vibrations when handheld devices are used. More elaborate haptics are often not combined with AR technology.

The immersion of AR is generally more limited because the user experiences contextual information, such as text, virtual objects, or sounds, which can be related to the environment, however, it lacks spatial mapping capabilities which creates less of a blend and more of an overlay. When it does include such capabilities, it moves towards the space of mixed reality (Parveau & Adda, 2018).

AR Technology

The definition given does not restrict AR to specific display technologies, such as head-mounted displays (HMDs), but allows for a wider range of displays and set-ups (Azuma et al., 2001; Carmigniani et al., 2011). Even though the specific technology that is used can differ, each AR system has a few key elements: a display or output device so the user can perceive both reality and the digital information, input to the system so the user can interact with the digital information (e.g. smartphone, controller, hand), tracking so the digital information is aligned with what the user is perceiving, and a computer that runs the software to manage everything (Berryman, 2012). Azuma et al. (2001) classify three categories for types of visual displays because these are often the basis or combined with other modalities, namely HMDs, handheld displays, and projective or spatial display (Azuma et al., 2001; Carmigniani et al., 2011).

HMD is a type of display that is worn on the head of the user which provides visuals of the real environment combined with digital information in front of their eyes (Azuma et al., 2001; Carmigniani et al., 2011). This can either be done through video see-through or optical see-through. Video see-through usually requires two cameras on the device to capture the environment which serves as the real-world background for the virtual AR overlay. Optical see-through creates a virtual AR overlay on a transparent display which allows for the user to see the physical world with the additional digital information (Azuma et al., 2001; Carmigniani et al., 2011; Normad et al., 2012). Optical see-through allows for a more natural way of perceiving the real world, however, video see-through allows for more control over the end results because the representation of the real world is already composed by the computer which can therefore be easier augmented (Carmigniani et al., 2011).

Handheld AR systems use relatively small computing devices with flat-panel LCD displays that use attached cameras to provide video see-through-based augmentations (Rekimoto, 1997). Similarly to HMD, the camera captures the real world as background with virtual graphics as overlay, additional information provided by sensors such as GPS are used to improve the experience (Carmigniani et al., 2011). The most common handheld systems are phones and tablets which are very accessible due to their portability and because they are so widespread (Schmalstieg & Wagner, 2007).

Spatial displays generally use video-projectors and tracking technologies to lay digital information directly over physical elements in the real world, without having to wear or hold a device (Bimber & Raskar, 2005). This set up allows a user, or a group of users, to benefit from digital augmentations in the physical world without obstructed interaction. However, due to the physical dependency it also experiences limitations such as the need for physical support to work and the possibility of limited immersion due to the brightness of the projector and the surface material (Roo & Hachet, 2017).

2.1.3 Mixed Reality

The "MR-centered view" considers MR as its own specific reality that creates a space in which both physical and virtual elements exist and start to blend together due its spatial awareness (Honig et al., 2015). In this space, virtual objects can be positioned relative to the physical environment, the user, or any other virtual or physical object. This is done through mapping the user's space in which 3D-embedded virtual content is presented in real-time. Because of its spatial awareness and the blend between worlds, the user experiences greater immersion (Kress & Cummings, 2017). Furthermore, the MR experience has to be user-centered which offers natural and immediate interactions with both the physical and virtual environment (Parveau & Adda, 2018). The objects, both physical and virtual, are responsive to the user and to each other creating a larger degree of interaction (Brigham, 2017; Speicher et al., 2019). The level of interaction allows the user to walk around virtual objects that are registered in space and to manipulate the MR environment (Speicher et al., 2019).

Similarly to AR, MR has a natural inclusion of haptic feedback due to the possibility of interacting with the physical world. In addition, haptics like haptic gloves can be added so virtual content can also provide feedback. However, these more elaborate types of haptics are more limited because the specific hardware is sparce, complex and costly (Melo et al., 2022; Wang et al., 2019). Even so, they are widely used in the medical field for train, especially surgical training.

MR Technology

Mixed reality has many similarities to augmented reality, in essence it can therefor also use the same displays as AR: HMD, handheld displays, or spatial display. However, the immersion of the user and natural interaction are important aspects of MR which some displays support better than others. The best immersion in combination with natural interaction has so far been achieved through HMDs which are therefore the most common choice to display MR (Parveau & Adda, 2018).

HMDs can be used through video see-through systems or optical see-through systems. As discussed in the section on AR, these systems have different ways of perceiving the physical world meaning they also have to implement the virtual content in different ways. Optical see-through systems have a more natural way of perceiving the physical world due to the see-through glasses (Carmigniani et al., 2011), however, it has a limited screen for virtual content, often consisting of a Field of View (FOV) of 40 degrees (Kress & Cummings, 2017). This can lead to a less immersive experience because the virtual content can be cut off at the edges of the user's vision. Video see-through systems have the benefit of having greater control over the environment (Carmigniani et al., 2011), in addition, they typically have a larger FOV of 90 to 110 degrees (Kress & Cummings, 2017).

To create an immersive MR experience, the system needs to have a form of spatial mapping capability, this is similar to the SLAM principle, "*Simultaneous Location and Mapping*" (Parveau & Adda, 2018). SLAM is the process of building a map of an environment while at the same time using the map to deduce the location of the system (Durrant-Whyte & Bailey, 2006). To do this, the MR system needs to be equipped with sensors, such as cameras, allowing it to create and use a map of the environment of the user. Depth mapping can be based on stereo vision, structured illumination, or Time of Flight (ToF) (Dunn et al., 2018; Kress & Cummings, 2017). ToF is quite common due to its ease of implementation, this allows the system to render a virtual representation of its environment and create an understanding of the space (Parveau & Adda, 2018).

2.1.4 Virtual Reality

For approximately the last decade, the goal of VR is to completely immerse the user in an artificial world (Brigham, 2017). This is done by occluding information of the user's physical environment and replacing this with computer generated virtual environment and provide the capability of interacting with this environment (Boas, 2013; Brigham, 2017; Rauschnabel et al., 2022) Whereas AR and MR try to overlay or merge the physical environment with virtual information, VR aims to hide the physical world as much as possible. Due to the occlusion of the real world, the user can typically only interact with virtual content through handheld controllers, as opposed to AR and MR where the user can also interact with the real world (Anthes et al., 2016).

Generally, VR can be considered as most immersive of the technologies, though there are different degrees of immersion based on the system, these systems can be categorized as non-immersive systems, semi-immersive systems, and fully immersive systems (Boas, 2013). In general, the focus of VR is on the last two types of systems to provide greater immersion to the user. In addition, it is important that the location of the user in the virtual environment is registered in such a way that it feels natural to the user. When moving through a virtual environment and the movements do not correlate to the expectations of the user, the immersion of the world will decrease, in addition it can lead to simulation sickness (E. Chang et al., 2020).

Immersion can also be increased with the use of multi-sensory feedback. In contrast to AR and MR, there is no natural haptic feedback so to provide this haptics are needed. These elaborate types of haptics offer 3D touch with 6 degrees-of-freedom (DoF) which allow touch to be simulated, get user's attention, and to guide users during procedures in for example medical training (Melo et al., 2022). Research has looked into adding olfactory and gustatory for greater immersion, however, they are very rarely used in XR applications because it can be complex and expensive to simulate. In addition, specific taste devices are basically nonexistent and if they already exist, they are very intrusive to the user (Melo et al., 2022).

VR Technology

VR is mainly experienced through headset-based applications, with some expectations like VR CAVEs (Boas, 2013; Lu & Smith, 2009; Rauschnabel et al., 2022). A CAVE is a virtual reality room that has projectors covering the walls of a room with stereoscopic images, for this the user needs to wear glasses that are synchronized with the alternating images. In addition, speakers are placed around the room to bring greater immersion (Boas, 2013). While part of VR, CAVEs are not used very often due to spatial and monetary constraints, in contrast to HMD which are more focused at end-consumers (Anthes et al., 2016).

There is currently a wide range of HMDs on the market, the simplest being a frame in which a smart phone can be placed with additional lenses mounted at a reasonable distance. These types fully rely on the technology that is used by the smart phone (Anthes et al., 2016). Other HMDs are more advanced and consist of stereoscopic displays and tracking systems that allow users to see 3D images through a large Field of View (FoV), usually of 110 degrees, which move accordingly to the user's head position (Anthes et al., 2016; Boas, 2013). VR headsets can range in DoF, meaning, the number of parameters in a system that can vary independently of each other. They usually have 6 DoF and support rotational and translational tracking (Rauschnabel et al., 2022). The majority of consumer HMDs are wireless headsets that run independently without a PC or mobile phone, an alternative are wired HMDs which allow for more powerful computing by the connected PC (Anthes et al., 2016).

When looking at input devices, users can interact with the use of controllers, wired gloves, tracking, and/or navigation devices (Anthes et al., 2016; Boas, 2013). The controllers are worn in both hands and provide, in addition to buttons or joysticks, 6 DoF tracking information (Anthes et al., 2016). Wired gloves give more precise input to the system which can provide more interaction, in addition the gloves can give haptic feedback to the user (Boas, 2013). Tracking can be done through for example computer vision, magnetic tracking, and/or Inertial Measurements Units, and is used to capture hand gestures or the posture of the user which can be important in order to provide a reasonable self-representation in the system (Badler et al., 1999). Navigation devices are used to give users the sensation of moving through the virtual environment. Often this is done through treadmills which can vary in the number of directions it allows the user to move in, from traditional on direction to omnidirectional treadmills (Anthes et al., 2016).

2.1.5 Overview of used definitions

As seen in the previous sections, defining X Reality, its framework, and the individual components is not a straightforward task. Numerous researchers have different definitions which are applied in all kinds of manners. Therefore, an overview of the definitions and how they will be applied for the remainder of this thesis is provided:

MR-centered view	The continuum on which Augmented Reality, Mixed Reality, and Virtual Reality are placed where each component has its own space and are distinguished by the level of immersion, interaction, and information.
X Reality (XR)	The umbrella term for the spectrum of Augmented Reality, Mixed Reality, and Virtual reality.
Augmented Reality (AR)	An overlay of virtual information on a physical real-world environment with limited to no relation between the virtual information and the real-world environment.
Mixed Reality (MR)	A blend of virtual information and the physical real-world environment where the virtual information is spatially related to the real world to create greater immersion.
Virtual Reality (VR)	A fully immersive virtual-world environment where real-world information is obscured.

2.2 Acquired Brain Injury

As this thesis focuses on using XR systems during motor rehabilitation of people who suffered an acquired brain injury (ABI), it is important to get a bet understanding of what an ABI is, what the effects are following an ABI, and what ABI rehabilitation looks like.

Acquired brain injury (ABI) is an umbrella term that includes a wide spectrum of brain injuries, usually divided into traumatic brain injury (TBI) and non-traumatic brain injury (Teasell et al., 2007). ABI is classified based on the severity: mild, moderate, or severe. Though depended on the severity, ABI often results in residual symptoms that affect the individual's cognition, movement, sensation and/or emotional functioning (Gardner & Zafonte, 2016; Giustini et al., 2013). Rehabilitation is an important aspect in the recovery process, though may require considerable resources and may take years, if patients fully recover at all (Gardner & Zafonte, 2016). New rehabilitation methods are explored though, including with the use of XR technologies. These technologies might offer new opportunities and benefits compared to traditional rehabilitation; this will be explored further in chapter 2.3.

2.2.1 Traumatic Brain Injury

Traumatic brain injury (TBI) is when the brain gets damaged due to an external physical force like a bump, blow, or jolt to the head or a penetrating head injury that disrupts the normal functioning of the brain (Gardner & Zafonte, 2016; Giustini et al., 2013). The cause varies with a main factor being the age of the individual which is also seen in the leading cause of TBIs, falls. For individuals over 64 years old, 81% of TBIs were the result of a fall, whereas for children under the age of 15 years, falls were the cause of 55% of TBIs (Gardner & Zafonte, 2016). Other important causes of TBIs are unintentional blunt trauma (e.g., being struck by an object), motor vehicle accidents, and assault.

The trauma can lead to different types of damage to one or more areas of the brain. TBI is often caused by accelerations or decelerations of the head that involve both linear and rotational forces. This can lead to damage in the brain at the site of contact (coup) and at the opposite side of the brain (countrecoup) due to inertial forces (Gardner & Zafonte, 2016). It can cause the brain to move within the cranial vault, the stretching and compressing can affect neuronal cell bodies, axons and organelles as well as glial cells. This can then lead to acute neurometabolic and neurochemical changes and dysfunctions and create a biochemical cascade disrupting the functioning of the affected areas of the brain (Giza & Hovda, 2001; Staal et al., 2007).

2.2.2 Non Traumatic Brain Injury

Non traumatic brain injury (nTBI) is when the brain gets damaged by something that happens inside the body, or a substance introduced into the body that damages brain tissues (Brain Injury Canada, n.d.). One of the main causes of a nTBI is a cerebral vascular accident (CVA), also known as a stroke, which is when the cerebral perfusion or vasculature are acutely compromised, in other words, when there is an interruption in the flow of blood cells to the brain (Khaku & Tadi, 2022). Other causes can be metabolic disorders, cerebral hypoxia after cardiac or respiratory arrest, subarachnoid hemorrhage, near-drowning experience, tumors, lead poisoning, etc. (Giustini et al., 2013).

While TBI usually only affects focal areas, nTBI can spread to all areas of the brain because it attacks the cellular structure (Giustini et al., 2013). Nonetheless, nTBIs are still more often focal injuries, likewise, strokes can be defined as an acute focal injury of the central nervous system by a vascular cause. About 85% of strokes are ischemic meaning there is a lack of blood supply, often caused by arterial occlusion, in rarer cases caused by occlusion of cerebral veins or venous sinuses (Campbell & Khatri, 2020; Khaku & Tadi, 2022). When a cerebral artery is occluded causing blood flow to decrease below a critical level, it leads to neuronal electrical function to cease and a clinical deficit to develop. However, in many patients the blood flow can be restored which reduces disability after ischemic stroke (Campbell & Khatri, 2020). The other 15% are hemorrhagic which are caused by the rupture of cerebral arteries, they can be intracerebral or subarachnoid which is often the result of a ruptured aneurysm. The most common cause of hemorrhagic stroke is deep perforating vasculopathy related to high blood pressure, it most often affects the basal ganglia, cerebellum, pons, or thalamus (Campbell & Khatri, 2020).

2.2.3 Severity

ABI severity is measured along a continuum and can be classified as mild, moderate, or severe (Gardner & Zafonte, 2016). The most used method to classify ABI severity is through the Glasgow Coma Scale (GCS) which tests three components, namely the postinjury eye movement, motor responses, and verbal responses (Ann Lieben et al., 1998). Each component gets a score that provides a rudimentary measure of someone's functional status, the sum of the scores determines the severity of the brain injury (Gardner & Zafonte, 2016; Giustini et al., 2013), see Table 1. (Teasdale Bryan Jennett, 1974). The severity classification describes the level of initial injury in relation to the neurological severity of injury caused to the brain. There is no direct correlation between the initial GCS and the short-term recovery or functional abilities (Giustini et al., 2013). In some cases, it is not possible to get an accurate GSC score, for example when an individual has used alcohol or other substances (Gardner & Zafonte, 2016).

The Glasgow Coma Scale (GCS)			
Best eye response		**Best motor response**	
No eye opening	1	No motor response	1
Eye opening in response to pain	2	Extension to pain	2
Eye opening to speech	3	Abnormal flexion to pain	3
Eye opening spontaneously	4	Flexion/withdrawal to pain	4
		Localizes to pain	5
Best verbal response		Obeys commands	6
No verbal response	1		
Incomprehensible sounds	2	**GCS score classifications**	
Inappropriate words	3	Mild ABI	13 - 15
Confused	4	Moderate ABI	9 - 12
Oriented	5	Severe ABI	≤8

Table 1 The Glasgow Coma Scale from Teasdale & Jennett (1974)

Mild ABI have a GCS score of 13-15 and is the most common form of brain injury, about 80% of all TBIs fall into this category (Gardner & Zafonte, 2016). The American Congress of Rehabilitation Medicine (ACRM) define mild TBI when an individual experiences loss of conscious of 30 minutes or less, a GCS score of 13 - 15, and the duration of posttraumatic amnesia (PTA) is no longer than 24 hours (ACRM, 1993). Other symptoms can accompany these criteria, however, when the injuries exceed these criteria, it is considered to be of more than mild severity (Giustini et al., 2013).

Moderate ABI have a GCS score of 9 - 12 and equally shares the remainder of the ABI cases, with moderate TBI's accounting for about 10% of all TBIs (Gardner & Zafonte, 2016). It is considered a moderate TBI when an individual experiences a loss of consciousness of a few minutes up to a few hours, confusion that lasts from days to weeks, and physical, cognitive and/or behavioral impairments that last for months or are permanent (Giustini et al., 2013). Individuals with moderate TBI can usually make a good recovery with the treatment, or they can successfully learn to compensate for their deficits (Maas et al., 2008).

Severe ABI have a GCS score that is lower than 8 and accounts for a similar amount of ABI cases as moderate ABI, with 10% of all TBI cases being severe TBIs (Gardner & Zafonte, 2016). Severe ABI is when disorders of low level of consciousness are experienced and may include coma, vegetative state, or minimally conscious state. Coma is when there is complete failure of the arousal system, whereas in the vegetative state there is preserved capacity for spontaneous or stimulus-induced arousal. The minimally conscious state does show discernible behavioral evidence of consciousness, however, remain unable to reproduce this behavior consistently (Giustini et al., 2013).

2.2.4 Effects

The long-term effects of ABI are heterogeneous and are determined by the severity of the injury, site and size of the injury, and by the extent of subsequent recovery (Gardner & Zafonte, 2016; Langhorne et al., 2011). Depending on these factors, an ABI can result in cognitive, physical, sensory, somatic, psychologic changes, or changes in personality (Gardner & Zafonte, 2016). The variety of effects are wide and generally correlated to the cause of the injury, to narrow it down, the focus will be on hemiparesis caused by a stroke due to the high number of affected people.

As mentioned, one of the most common effects of a stroke is hemiparesis, muscle weakness on one side of the body, when a person experiences complete paralysis on one side of the body, it is called hemiplegia, about 70-85% of first strokes are accompanied by one of these forms (Langhorne et al., 2011; Weishaupt & Sachdev, 2021). Hemiparesis can affect an individual's face, arm, and leg on one side of the body which can in turn cause trouble maintaining balance, standing, walking, grabbing objects, and more generally moving with precision. These effects are more generally connected to a lack of coordination and muscle fatigue (Weishaupt & Sachdev, 2021). All these actions are part of activities of daily life (ADL), hemiparesis therefore affects all basic activities greatly, think of dressing oneself, eating, and walking, which can therefor also greatly affect someone's social life. This decrease in ADL independence also impacts the patient's quality of life greatly. Studies have shown that a stroke victim's life satisfaction and quality of life were significantly lower than those of control groups consisting of people who hadn't suffered a stroke (Haley et al., 2011; Laurent et al., 2011).

Independence is also correlated with being able to move around freely, however, walking dysfunction occurs in most stroke patients of whom 25% have residual gait impairments despite of rehabilitation (Li et al., 2018). Gait abnormality is characterized by a presentation of gait asymmetry, decreased walking speed, and the stride length is shorter. Furthermore, they usually have decreased stance phase and prolonged swing phase of the affected side. The combination of gait abnormality and muscle weakness increase the risk of falls for stroke survivors (Li et al., 2018). To improve the quality of life, increasing one's mobility and therefor also their independence is an important goal, which can be done through rehabilitation.

2.2.5 Rehabilitation

ABI rehabilitation starts after the stabilization of basic life functions, in the case of a stroke usually 48 hours after onset (Dobkin, 2004; Giustini et al., 2013). Stroke rehabilitation usually consists of a cyclical process including assessment to establish the patient's needs, goal setting to define realistic and achievable goals for improvement, intervention to support reaching those pre-defined improvements, and reassessment to evaluate the progress of the patient (Langhorne et al., 2011). While there is limited evidence of enhancing true neurological repair in the brain, there is strong evidence that task-oriented training can support the natural pattern of functional recovery. This supports the view that functional recovery is mainly driven by adaptive strategies that aim to learn to compensate for impaired body functions and by doing so lessen limitations in daily life (Langhorne et al., 2011). An important factor for good outcomes seems to be associated with high patient (and family) motivation and engagement (Govan et al., 2008; Langhorne et al., 2011).

Generally, a multidisciplinary team is established as the basis for delivery of stroke rehabilitation. Mobility and speech interventions should begin as soon as possible after the onset where physical, occupational, and speech therapists will primarily build skills and change the environment of the patient to let them stay home with as little care support as possible (Dobkin, 2004). Furthermore, supportive social and psychological services, the removal of architectural barriers for easy mobility in house, and devices such as wheelchairs and walkers are offered to patients and continue to play an important part in helping patients to adapt to their disability (Dobkin, 2004)

The intensity of motor rehabilitation varies a lot between patients and is dependent on the severity of the injuries and the setting of the patient (Schaechter, 2004). Recovery of motor function when receiving rehabilitation is generally most rapid in the first month after the onset of the stroke, to slow during the subsequent months, and to plateau 6 months after onset (Hendricks et al., 2002). After these 6 months, approximately 50-60% of stroke patients still experience some degree of impairment, and about 50% are at a minimum partially dependent in activities of daily living (Dobkin, 2004; Hendricks et al., 2002; Schaechter, 2004).

Standard motor rehabilitation after a hemiparetic stroke usually consists of a mix of approaches, including neurofacilitation techniques, and task-oriented training (Schaechter, 2004). Neurofacilitation techniques aim at retraining motor control by encouraging natural movements with the affected body parts and inhibiting abnormal movements. Task-oriented training aims at improving a certain skill by performing selected movements or functional tasks while also considering the interplay of many systems like musculoskeletal, perceptual, cognitive, and neural systems (Schaechter, 2004). Task-oriented training includes a wide range of interventions such as treadmill training, walking training on the ground, bicycling programs, endurance training, sit-to-stand exercises, reaching tasks to improve balance, and grasping objects (Rensink et al., 2009). Results showed that training was more successful when it was related to a task because it is more relevant for the needs of the patient (Langhorne et al., 2011; Rensink et al., 2009).

2.3 Motor Rehabilitation with XR

The emergence of XR systems allowed for new forms of rehabilitation to ABI patients, especially motor rehabilitation (Colomer et al., 2016). These new ways of training can be valuable and are able to provide substantial benefits, not only to motivate patients to take part of treatment for a longer period, but also to standardize the quality of treatment (Fong et al., 2022; Leong et al., 2022). In addition, research has shown that training in enriched environments can lead to better problem solving and performance of functional tasks than training in basic environments. These are important aspects of motor rehabilitation, so because XR can provide enriched environments it has the potential to promote rehabilitation (Laver et al., 2011). Even though HMDs have experienced immense technological advances over the last 10 years creating more user-friendly interfaces, increased immersive potential, and lighter hardware, most research on XR during rehabilitation uses low-tech screen-based output devices instead of HMDs. The main reasons provided are due to the low costs, the commercial availability, and the fact that patients are usually familiar with their operation. However, HMDs can offer an advantage in representing the depth of motion in 3D space and they can be considered more portable because there is no need for a full set- up which also save in costs (Butz et al., 2022).

To gain a better understanding on how XR is used during ABI rehabilitation, its effect on the rehabilitation process will be discussed. In addition, varying examples of how XR systems are used during the rehabilitation are provided. Because motor rehabilitation is often divided into upper limb and lower limb rehabilitation, this division will also be applied in this section.

2.3.1 Upper Limb Rehabilitation

For upper limb rehabilitation the focus is often either on enhancing coordination and body control, and/or to improve ADL skills. Studies showed promising results of the application of XR fort upper limb motor rehabilitation (Colomer et al., 2016; Levin et al., 2015; Phan et al., 2022; Saposnik & Levin, 2011). It can be considered a feasible alternative since the movement kinematics when reaching, grasping, transporting, and releasing objects in a XR environment are comparable to those in the physical world, especially in AR and MR systems where the real world is still part of the environment (Colomer et al., 2016). Several controlled trials using VR even suggested that the additional use of VR systems in the upper limb rehabilitation improved upper limb function and performance in ADL to greater extent than the same dosage of conventional therapy (Turolla et al., 2013). Similarly, in the systematic review on the use of AR and VR for hand rehabilitation, Pereira et al. (2020) found that the majority of research showed greater improvements compared to the control group. These improvements were found in an increased range of movement of thumb IP joint, pinch and grip strength, performance in paretic arm speed, the precision of movements, execution times, and efficiency of functional tasks (Pereira et al., 2020).

Colomer et al. (2016) designed a set of AR upper limb task-oriented exercises using a projective tabletop system that allowed for multitouch interaction with the hands or by manipulating tangible objects. The focus was on arm and hand movements, mostly the flexion and extension of the elbow and the wrist, that the patient would make in daily living tasks, think of grating a vegetable, squeezing a sponge, to sweep crumbs of a table, or knocking on doors. Their results showed positive physical progression and high levels of participation, suggesting greater motivation compared to conventional therapy. Another XR approach is seen in the study by Huang et al. (2019) who used an immersive VR system to create a realistic experience to train the upper limb functioning. They used six programs, some consisting of practicing ADL such as in the kitchen, while others consisted of more recreational activities like on the basketball court (Huang et al., 2019). For this study they used controllers, meaning it could be used for general arm movements, however, hand and finger movements could not be trained. Ögün et al. (2019) solved this by combining an immersive VR system with a motion tracker, the Leap Motion. Patients used the VR system to play task-oriented games that focused on gripping and handling objects, the Leap Motion allowed users to manipulate virtual objects without the use of any external devices. They used a variety of games such as decorating a tree with leaves, picking up vegetables from bowl, and a kitchen experience game. The training using this system improved functional activities of the upper extremity, functional independence, and self-care skills in the patients (Ögün et al., 2019).

2.3.2 Lower Limb Rehabilitation

Lower limb rehabilitation often focusses on improving the gait (e.g., stride length, gait speed, endurance), dynamic balance, and fall efficacy (Yoo et al., 2013). Several research have shown that AR interventions could help to improve their lower limb dynamic balance, muscle strength, fall efficacy, and various gait variables such as speed and endurance (H. Chang et al., 2022). Similarly, VR systems have shown improvements in functional balance, gait velocity, cadence, stride length, and step length compared to conventional therapy. Other aspects were at least as effective as conventional therapy (Gibbons et al., 2016). This is also a conclusion Morel et al. (2015) came to, while some studies showed greater improvements compared to conventional therapy, not all found significant differences. However, they did all show at least similar progress while adding motivation with an entertaining training tool (Morel et al., 2015).

One way XR is used in lower limb rehabilitation is by combining the XR system with treadmill training. For example, Kim et al. (2015) tested the effects of treadmill training combined with non-immersive VR training. They placed a screen with video projector in front of the treadmill, on the screen they showed a 'VR video' which was responsive to the user, so when they increased their speed the speed of the VR video was also increased. The exercise consisted of community ambulation, such as walking on sidewalks, level walking, slope walking, and walking over obstacles. Their results showed significant improvements in the postural sway path length and speed, and in multiple balance measures compared to the control group who received conventional therapy suggesting that VR treadmill training has a positive effect on static balance measures (N. Kim et al., 2015). A different approach was shown by Lee et al. (2015) who focused on postural control training using an AR HMD. The patients had to practice alternating weight bearing and stepping motions on each side while they could watch modelled movements to compare their movements with the normal movements. Their results showed significant improvement in gait velocity, step length, and stride length compared to the control group who received conventional therapy (Lee et al., 2014).

2.4 Comparison Microsoft HoloLens 2 and Meta Quest Pro for Motor Rehabilitation

HoloMoves uses mixed reality to provide their services to rehabilitation centers, hospitals, and other care facilities. Currently they are using the Microsoft HoloLens 2 as platform which is an optical see-through system. At the same time, new hardware is being released that allow for mixed reality to be shown on virtual reality headsets using video see-through, such as the Meta Quest Pro. While both types of systems support mixed reality, their different displays can influence the experience in ABI rehabilitation. To get a better understanding in the differences and similarities and how they may influence stroke rehabilitation, both systems will be discussed in more detail followed by a comparison.

2.4.1 Microsoft HoloLens 2

The Microsoft® HoloLens is an optical see-through HMD delivering an immersive mixed reality experience to the user, see figure 3 (Microsoft, 2019; Palumbo, 2022). The first generation of HoloLens was released in 2016 and got considerable attention due to its advanced capabilities at the time (Liu et al., 2018). In November 2019, Microsoft released its successor, the HoloLens 2, which is an upgraded version in terms of hardware and software (Palumbo, 2022).

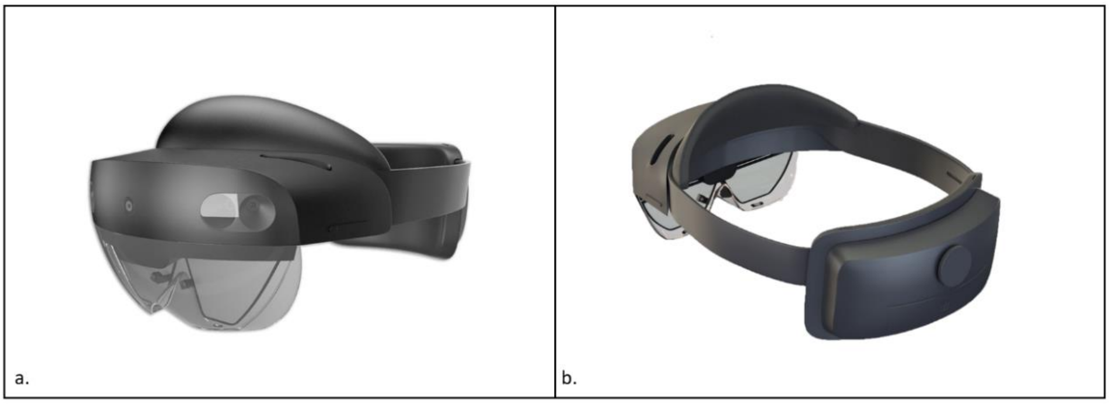


Figure 3 Pictures of the Microsoft HoloLens 2 where a. shows the front view and b. the back view of the headset

To create an immersive experience for the user it is important the system can provide a blend between the real world and the virtual elements added to it. Because the HMD has an optical see-through design, the real world does not need to be simulated, however, to create the desired blend the system needs to have a form of scene understanding. This is done through generating a representation of the environment, the HoloLens 2 has a few options depending on the intended application (Microsoft, 2022). The simplest version is by computing primitives that are representations of flat surfaces in a room, a surface is called a quad in these scenarios. The flat surfaces are areas on which holograms can be placed, however, it doesn't allow for occlusion of virtual objects behind real world objects. When occlusion of virtual objects is required, a watertight mesh is laid over the environment to generate a planar representation of the environment. This would allow the system to understand the 3D shape of objects and be able to occlude virtual information behind those objects. In addition, the detailed information also allows for more natural physics to be applied like objects hitting and interacting with a surface. However, because it requires more computing it can lead to increased latency (Microsoft, 2022).

Hardware

The HoloLens 2 consists of see-through holographic lenses through which the user can view the real world with the possibility of adding virtual content using its binocular waveguide display (Microsoft, 2019). This technology is based on the glass reflecting light within the lens so that the light of digital information enters the user's eye at the same time as light from the real world (Kress & Chatterjee, 2021). However, because of this the system is sensitive to bright light so when it gets too bright, the user is no longer able to see the content on the display very well (VRX, 2023b).

The FoV is 43° horizontally and 29° vertically (Brown, n.d.-b). While this is sufficient when the user is looking at virtual objects from a distance, when the user comes closer to an object the limits of the display are noticeable and parts of the 3D objects are no longer visible. However, because of the optic see-through display there is a natural blend of what is seen through the lenses and what is seen in the peripheral vision without any occlusion.

The headset has a total of 6 different cameras placed on the visor of the headset and 2 eye tracking cameras on the inside. To be able to map the environment, there are 4 tracking cameras placed facing the front and periphery of the user, with additional Inertial Measurements Units (IMU) consisting of an accelerometer, gyroscope, and magnetometer. The depth is measured through a camera in the front that uses Time-of-Flight sensors for near and far range. Last it has a RGB camera facing the front (Cooley et al., 2022; VRX, 2023b).

2.4.2 Meta Quest Pro

The Meta Quest Pro is a virtual reality headset that is manufactured by the company Meta and was released in October 2022, see figure 4 (Brown, n.d.-a). It is mainly targeted towards enterprise customers with various improvements over their consumer-focused headset, the quest 2.

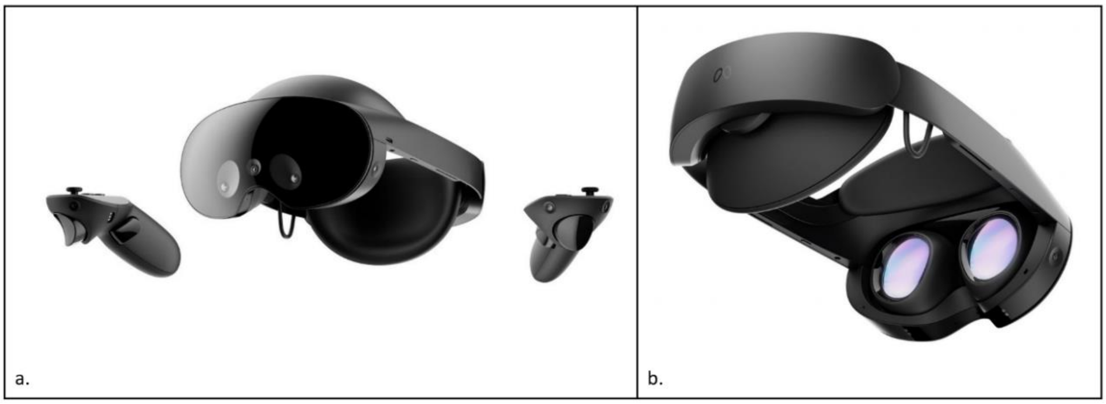


Figure 4 Pictures of the Meta Quest Pro where a. shows the front view and the optional controllers and b. the back view of the headset

The VR headset is focused on providing an immersive mixed reality experience using passthrough technology. To make the passthrough experience comfortable, it needs to convey a natural sense of depth which can't be done by showing a simple 2D video of the surroundings, it needs to digitally reconstruct the room as a 3D space (Meta Quest, 2022). One way the Quest Pro does this is by providing stereoscopic color passthrough, meaning, the images shown are rendered to the individual eyes from two separate angles providing stereoscopic cues. At the same time, the system uses algorithms for image-based rendering, stereo geometry reconstruction, and depth understanding to establish the location of objects in relation to the scene within a given room. This is done by producing up to 10.000 points per frame up to five meters away to create a dense 3D and temporally stable representation of the space. This enables the headset to pinpoint the location of objects in 3D space and to determine the location of the headset in the room (Meta Quest, 2022).

Another important part of mixed reality is the scene understanding so virtual content can be blended into the physical world. The system uses the previously described recreated 3D scene to place anchors in the room. An anchor is a simple geometric representation of an object (e.g. floor, ceiling, walls, desk, couch) with additional semantic labels attached. This is created through scene capture where the user walks through the room to generate the scene model and place anchors (Meta Quest, 2022). Similarly, virtual objects can be anchored in the space to create a seamless blend. These anchors then also allow for real-time occlusion of real objects by virtual content.

Hardware

The Quest Pro makes use of pancake lenses, a multi-element lens design that reduces the required distance between the display and the lenses, and subsequently the depth profile of the headset itself (Brown, n.d.-a). The FoV visible to the user is 106° horizontally and 96° vertically which covers the majority of the FoV of the human eye to create great immersion.

By default, the headset does not fully enclose the wearer from the physical world but has a gap at the bottom and sides of the headset. This is an intentional choice by Meta because the focus is on enterprises that will use the system mainly as a mixed reality system. The system does come with side-mounted gaskets that can be magnetically attached to the headset to create full immersion (VRX, 2023a).

The system has an inside-out tracking system with 5 internal cameras and 5 tracking cameras. It provides eye and face tracking through the 5 internal cameras, an eye tracking camera per eye, on tracking the upper face, and two tracking the lower face. The eye tracking allows for dynamic foveated rendering, this uses eye tracking to optimize the graphical performance to where the eyes are looking and blur the peripheral view of the user to create a more natural experience (VRX, 2023a). The 5 tracking cameras are used to map the environment and hands of the user, it has three front-facing and two side-facing cameras.

2.4.3 Comparison of Headsets

When looking at the headset, both headsets have the battery pack at the back of the band to distribute the weight, however, the HoloLens is 566 gr whereas the Quest Pro is 722 gr which can influence the comfort of wearing the headset (Brown, n.d.-b). Some reviews noted that after prolonged use of the Quest Pro, they experienced headaches due to the weight pressing in on their forehead. This can be because the front weight of the headset is centralized on the forehead cushion as opposed to a facial pad-rim or a top strap. However, the HoloLens 2 also rests mainly on the forehead and is generally praised for its comfort, so the discomfort could also be because of the increased weight of the Quest Pro. This discomfort led to the users loosening the headset which removed some immersion, in addition, it could lead to the headset slipping during more active use (VRX, 2023a). This could be troublesome during rehabilitation because the user is expected to move around, either seated or by walking through the room.

A clear difference between the headsets is that the HoloLens 2 has an optic see-through visor that allows for the user to see the real world directly, also when it is turned off, whereas the Quest Pro does not allow for this. The user is occluded from the real world when wearing the Quest Pro unless the pass-through function is active. Because of this occlusion, the user is not able to have direct eye contact with other people while wearing the headset. In addition, while there is a visor, the HoloLens 2 does allow for this eye contact with others, in addition, the visor can easily be flipped up and down which allows for this possible barrier to be easily removed (VRX, 2023b). In contrast, the Quest Pro needs to be removed completely to be able to have direct eye contact with others, or to see the real world directly. This could influence the rehabilitation experience when wearing the XR device. During rehabilitation the therapist is often helping the patient during the exercises, through this process, trust and communication is important. Therefore, by removing direct eye contact it can influence the connection between the patient and the therapist, in addition it can be harder for the therapist to judge how the patient is feeling and know when they might need to step in. This can be seen as a huge drawback for physical therapy which raises the question whether the advantages of the Quest Pro outweigh this disadvantage.

This difference in viewing the world also influences the FoV of the devices. The FoV of the Quest Pro is 106° horizontally and 96° vertically which makes it considerably larger than the HoloLens 2 with a FoV of 43° horizontally and 29° vertically, see figure 5. What is important to note here is that the FoV of the HoloLens 2 is only the space where additional virtual content is shown, however, the rest of the FoV of the human eye is not occluded meaning that the rest of the world can be seen in a natural sense. In contrast, while the FoV of the Quest Pro is a lot larger, it does have a black frame around the screen that can be seen in the peripheral vision with a sliver of the real world around it. This black outlining is in the outer edge of the peripheral vision making it not very noticeable when using the device, especially when focusing on a task or game presented on the device, it is a similar experience as wearing regular glasses. Even with this visible edge, the immersion of the Quest Pro is generally greater because of the larger FoV compared to the smaller FoV of the HoloLens 2 (VRX, 2023b).

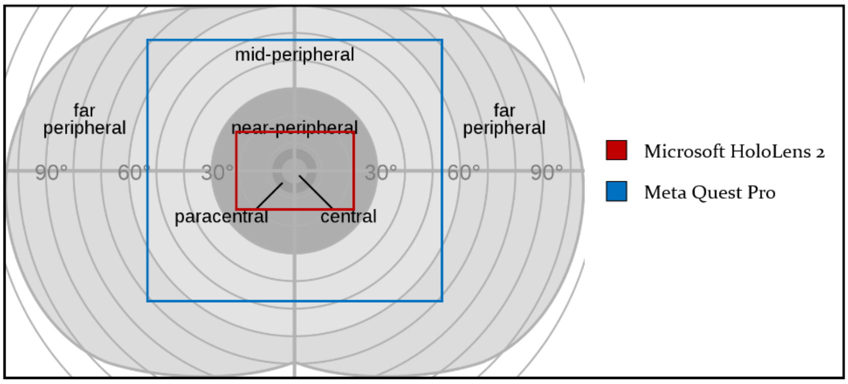


Figure 5 Comparison FoV of the Microsoft HoloLens 2 and the Meta Quest Pro relative to the human FoV

Both headsets support eye and hand tracking (Brown, n.d.-b), especially hand tracking is an important aspect for easy use and for rehabilitation. It allows for more natural interaction without controllers, in addition, people can hold themselves for support when needed which can therefore be safer during rehabilitation. However, the techniques that support hand tracking differ between the two systems leading to a difference in performance. The HoloLens 2 uses a Time-of-Flight (ToF) camera which emits an infrared light signal, measures how long the signal takes to return, and then determines the depth based on extracted data. In contrast, the Quest Pro uses inside-out cameras to detect the position and orientation of the users' hands and the configuration of their fingers which are then tracked and oriented using computer vision algorithms. Both options have their pros and cons, so when looking at rehabilitation functions, the use of computer vision algorithms can be more successful in detecting hands when placed on a surface which can be more challenging when using a ToF camera. This is especially relevant in ADL rehabilitation when patients struggle to move their arms and hands from the table and the system needs to be able to detect the hand movements on the surface of the table.

Furthermore, while both systems add virtual information to the real world to merge worlds, video see-through is also able to alter real world characteristics. It is able to apply certain styles and tints to the real world, think of applying a color overlay to the feed, rendering edges, customizing opacity, and posterizing (Oculus VR, 2021). Moreover, because the HoloLens 2 uses optical see-through, the real world is still somewhat visible through the virtual content that is added so objects in the real world cannot be hidden. On the contrary, the Quest Pro can have a virtual overlay over the real world, which is able to hide them from the user, this gives greater control over the mixed reality that is shown.

When looking at the interaction with the virtual content, the experience is partially dependent on the depth perception of the device, when this is off it could cause unnatural interaction. Ballestin et al. (2021) did a comparison between an optical see-through HMD and video see-through HMD to see if there was a difference in the interaction in the peripersonal space, they found that without contextual information, the HMDs had similar underestimations of depth, but that video see-through HMD had more deviations along the x and the y-axis. When contextual information was added the optical see-through HMD and video see-through HMDs showed negligible differences in terms of accuracy (Ballestin et al., 2021).

Where Ballestin et al. (2021) did find a difference though, was in the experienced simulation sickness that is caused by wearing a HMD. Simulation sickness is mostly seen in VR systems where there is a mismatch between visual motion cues and the experienced motion. MR can have this as well, where video see-through can cause more simulation sickness than optical see-through due to the latency in the video stream (Ballestin et al., 2021). This can mean that the Quest Pro might lead to more simulation sickness compared to the HoloLens 2.

2.5 Overview Comparison XR Characteristics

To get a better understanding of the capabilities of AR, MR and VR and how these are represented in the Microsoft HoloLens 2 and the Meta Quest Pro, an overview was made with important characteristics that define the system and what might be relevant in rehabilitation, see table 2. This information is useful when comparing the effects of the systems when used during rehabilitation.

Noteworthy differences are that the Quest Pro is able to mix in a representation of real-world content instead of content that has a more virtual look, in addition it is able to occlude real-world objects with virtual information which the HoloLens 2 cannot do because it shows more see-through virtual content. However, the Quest Pro also has more risk of simulation sickness which is related to an influenced balance, and collision with real-world objects when they are occluded or when the pass-through is turned off.

		Augmented Reality	Mixed Reality	Virtual Reality	Microsoft HoloLens 2	Meta Quest Pro
Basis	Optical see-through reality	X	X		X	
	Video see-through reality	X	X			X
	Virtual			X		X
Added Content	Window (e.g., text window)	X	X	X	X	X
	2D Information	X	X	X	X	X
	3D Information	X	X	X	X	X
	Real world representations		X			X
	Occlusion of information	X	X			X
Content Spatial Positioning	Head-stable	X			X	X
	Follows user	X	X	X	X	X
	World-stable	X	X	X	X	X
Interaction	User x Virtual content	X	X	X	X	X
	User x Physical environment	X	X		X	X
	Static virtual content x Physical environment		X		X	X
	Kinetic virtual content x Physical environment		X		X	X
Hazards	Simulation sickness		X	X		X
	Collision			X		X
	Affected balance		X	X		X
Other	Eye contact with others	X	X		X	
	Transparent virtual content	X	X		X	
	Type of controls				Hand and gaze tracking, voice	Hand and gaze tracking, voice, controllers
	Type of hand tracking				ToF using infrared	Computer vision algorithms
	Size of FoV				43° x 29°	106° x 96°

Table 2 Comparison between characteristics of XR systems, the Microsoft HoloLens 2, and the Meta Quest Pro.

3. Objectives and approach

For the past decades, XR has developed rapidly allowing for numerous applications, such as in the field of motor rehabilitation. As previously discussed, studies have shown that the use of XR technology has the ability to increase motivation during rehabilitation in ABI patients. In addition, several studies even suggest greater improvements in motor function after rehabilitation with the use of XR training. However, these studies rarely give motivation for their selected use of XR technology even though their characteristics differ greatly possibly leading to different experiences. This is especially seen in the space of mixed reality where both optical see-through and video see-through are options, however, little is known about their different effects on rehabilitation. Understanding how these different technologies influence the experience of ABI patients and their therapists during rehabilitation can help increase the quality of rehabilitation with the use of MR.

In this thesis the focus will be on motor rehabilitation for ABI patients in general rather than one of the subgroups of ABI. This was decided as these patients often receive similar, if not the same, treatment as this is based on their symptoms rather than on the type of ABI. By not narrowing down the subjects, the results will eventually also be applicable to a larger group.

3.1 Objectives

3.1.1 Primary aim

The primary aim of this research is to investigate the following research question: *How do the differentiating features of optical see-through and video see-through affect the experience of motor rehabilitation of ABI patients from the perspective of the patient and the therapist?*

3.1.2 Secondary aim

As the experience of the ABI patient is not only influenced by the hardware used but also the game that is played, a game should be designed that takes the differentiating features into account while still staying relevant for ABI rehabilitation. This design process follows the Activity-Centric Design method as explained by Waern et al. (2022) where the focus is on targeting the user's experience through designing and influencing the activity of the user, rather than focusing solely on the design of the technology itself (Waern et al., 2022). However, as previous work regarding XR has mostly been done with low-tech screen-based output devices rather than HMDs, there is currently scientifically little known about how the MR systems differ and how this might play a role in the experience of users (Butz et al., 2022).

Therefore, the secondary aim is to first get a better understanding of the technical specifications of the headsets and the subjective importance of the individual differentiating features, which can then be used as input for designing a game for ABI rehabilitation.

3.2 Approach

The approach is based on the framework for developing and evaluating complex interventions presented by the UK Medical Research Council and the National Institute of Health Research (Skivington et al., 2021). This framework divides complex intervention research into four phases: development, feasibility, evaluation, and implementation. Research can start at any phase depending on the goal of the research. In addition, the framework defines a set of core elements that should be considered in each phase.

The development phase refers to the development of the whole process of designing and planning an intervention, from initial conception through to feasibility, pilot, or evaluation study. This is the phase during which this method is written and prior to actually starting the research, furthermore, it should be revisited throughout the research.

Stage 1: Context exploration

One of the core elements is to understand the context of the intervention. Similarly, this is an important aspect of Activity-Centric Design, to understand the context of the activity in which the technology will be employed. Therefore, to get a better understanding of the context and the needs and experiences of ABI patients, exploratory research will be conducted. The exploratory research consists of interviews with ABI patients and therapists who work with ABI patients to understand their view of traditional rehabilitation.

Stage 2: Investigation differentiating features

Next, in the background study a set of differences were found between the headsets that will be used in this thesis. However, this set currently lacks information on the importance and how they might each separately influence the experience of users. This information is of importance to create a well thought out game design for rehabilitation. Therefore, tests will be designed to create a better understanding of the technical specifications of the headsets which will allow to explore the potential design possibilities in the next stage. In addition, the results on how individual features might influence the experience of users can help explain results in later stages.

Stage 3: Design of game

HoloMoves has developed a game for upper limb motor rehabilitation of ABI patients which will be used as inspiration for creating a game design that can be used for testing the experience of ABI patients. To make it suitable for testing and answering the main research question, alterations will be made. These alterations will be based on the findings of the context exploration and the investigation of the differentiating features.

Stage 4: Experience of ABI patient

Last, to test how the differentiating features influence the experience of ABI patients with motor rehabilitation, the game will be tested in a within subject setting. A convergent mixed method approach will be used to gather different types of data that support and help explain each other to create a sound answer to the research question. This stage is part of the evaluation phase of the previously explained framework that is being employed which will allow for me to answer the research question. In addition, it will provide advice for the implementation phase which answers questions on the application of the results which will be discussed in an overall discussion.

4. Context Exploration of ABI Rehabilitation

Understanding the current experiences and needs of the user for whom the design is made serves as the basis of a design process according to the Activity-Centric Design method. Similarly, this is an important element to understand the preferences of ABI patients and therapists when employing mixed reality for rehabilitation. The goal for the context exploration is therefore to create a better understanding of the current experiences with rehabilitation/therapy and the use of technology in this process of both ABI patient and related therapists through semi-structured interviews. This information will be used as input for design choices for tests later in this thesis, and to help explain results that will be gathered.

4.1 Method

4.1.1 Participants

For the interviews, therapists and ABI patients will be gathered at rehabilitation center Roessingh. For the therapists the only inclusion criterium is that they should work directly with ABI patients. For the patients the only inclusion criterium is that they should receive rehabilitation for at least 2 weeks to have sufficient experience with rehabilitation that they could share.

4.1.2 Materials

For both the therapists and the ABI patients, a set of questions are made as a general guide during the interviews. For the interviews with the therapists the topics are on what they find important during rehabilitation and therapy, what their relationship with patients is like, and their experiences with technology during rehabilitation. The topics for the patients are similar, they included topics like how they experienced rehabilitation and therapy, what they find important, how they experience their relationship with their therapists, and how they experience using technology during rehabilitation, see Appendix 12.1 for the complete set of questions.

4.1.3 Procedure

The interviews will take place at rehabilitation center Roessingh. The participants will be informed about the purpose of the study. Afterwards the interview will start. The interviews take approximately 15-20 minutes.

4.1.4 Measures

To measure the qualitative experience of therapists and ABI patients, the interviews consist of predefined questions as a guide through the interviews, in addition, follow up questions will be asked on interesting answers. As previously described in materials, the therapists and patients each have their own specific set of questions that will be used during the interviews. The audio of the interviews will be recorded using the researcher’s phone and afterwards transcribed.

4.2 Results

For the interviews, 2 therapists (1 occupational therapist age 33 and 1 physiotherapist age 44), and 2 ABI patients (1 woman age 69, and 1 man age 55), who both suffered a stroke, were interviewed. Before approaching the patients, their responsible doctors were asked and granted permission to include the patients. Before the interviews started the patients were informed and gave consent to participate.

4.2.1 ABI Patients

The interviews consisted of 4 main topics: their rehabilitation experience in general, their experience with occupational/physical therapy, the interaction with healthcare professionals, and their take on technology for rehabilitation.

Both patients have a positive experience with their rehabilitation in general. They are very positive about Roessingh and explained it felt safe, trusted, and pleasant. Furthermore, they enjoy the groups they were placed with as they provide motivation to the other group members to push themselves further. The main source of motivation is to get back to partake in regular life. Getting back the confidence, energy, and capability of doing their hobbies and profession are sources that really let them push their boundaries. This is also supported at Roessingh where therapists provide them with resources to be able to reach those goals as best as they can.

They experience the occupational and physical therapy as well adjusted to their needs and level of capabilities. While being clinically admitted their schedules are quite full of almost every hour a different type of therapy. After being released they receive about 2 times a week physical therapy, once a week occupational therapy, and once a week fitstroke which trains the cardio of the patient. They explained they don't experience any frustrations with rehabilitation or therapies, the only frustrations they mentioned are with their own bodies when something wasn't working as they would want it to work.

They are also very positive about their interaction and connection with the healthcare professionals. The healthcare professionals really build a bond with the patients and get to know them which creates a safe atmosphere. The therapists try to push patients to their limits and make sure patients take a break when they feel it's necessary.

At Roessingh, quite a lot of different technologies are used during rehabilitation, think of a zero G harness which allows patients to walk and catch them when they fall, machine to support arm movements, and treadmills with obstacles to train and measure balance during walking. They explained they are open to any type of technology as long as they are capable of using it and it's beneficial to their rehabilitation.

4.2.2 Therapists

Similar to the interviews with the patients, the interviews consisted of 4 main topics: their view on rehabilitation in general, their role specifically, the interaction with patients, and their take on technology for rehabilitation.

Both therapists argued that the connection with the patient is one of the most important elements of rehabilitation. It is the first step which needs to be taken from that point forward they can set goals and motivate the patients. A different important element is to protect the safety of the patient, especially because the body of the patient has already let them down, so it is important to give a sense of safety and confidence that nothing is going to happen to them.

The goal of therapy is to get the patient to a point where they can live independently in a safe manner. This looks different for everyone, so the advice and goals get adjusted to each patient. The therapies get adjusted to the interests of the patients, for example, if they are interested in gardening than the occupational therapist will try to decipher which movements are needed for that and train those movements with the patient. The therapists sometimes also need to step in, for ABI patients this is often due to fatigue. They judge when this is needed by looking at the complexion of the patient, for example when the gaze wanders, and by the quality of movements.

They see patients both during individual appointments and during group sessions. Groups will often consist of 3 to 6 patients with 1 therapist for every 3 patients.

At Roessingh they use the innovation lab which uses technology to train upper limb function. They try to have something for every level of patient, think of a robot that supports patients who have very low upper limb function. Furthermore, the user friendliness is an important element of adopting new technologies for rehabilitation and if the patients are able to translate the movements to daily life.

4.3 Implications

From the interviews it can be concluded that the main motivator for patients is to get back to daily life with confidence and in a safe manner. This is also recognized by the therapists who try to implement this into therapies as much as possible. It shows that the focus is on the connection with the patients which in return is felt by the patients. Furthermore, safety in general is an important theme as it is one of the main goals of the therapists to nurture and is therefore reflected in the employment of technology. This safety is partially supported by the ability to know when the therapist needs to intervene during therapy. The complexion of the patient and the quality of movements are important indicators for this. For the remainder of this study the connection between the therapist and patient, and the ability to read the emotional state of the patient are important elements to consider in the tests.

5. Investigating the Differentiating Features of Mixed Reality Headsets

The previous chapter explains the first-hand experiences of ABI patients and their therapists which serves as important input in the design process for a game for rehabilitation with the use of MR. In addition, an understanding of the hardware that will be used is important to create a good experience for the user. However, as discussed in chapter 2.3, most research on XR during rehabilitation uses low-tech screen-based output devices instead of HMDs resulting in no clear description of how MR and its individual characteristics might influence the experience of ABI patients or users in general.

A better grasp of how the MR technologies differ from each other should be created. In chapter 2.4 the HoloLens 2 and Quest Pro were explained and compared to identify the potential differences between the headsets. The next step is to create an understanding of what the relevance is of these individual differences and how they might affect the experience of users in general. This can aid in the design process of creating games and rehabilitation with the use of MR.

Therefore, the goal is to measure the influence of the unique individual features that might differ between the HoloLens 2 and the Quest Pro on the experience of users in general. To be able to measure those features, two separate tests were made to fit the features, the FoV test and the Cooperation test, with as umbrella term the Design exploration tests, see Table 3.

(Possible) differences based on literature	**Tested in**
Field of View (FoV)	FoV test
Spatial awareness of user	FoV test
Ability to have direct eye contact with others	Cooperation test
Clarity of virtual content	Cooperation test
Simulation Sickness	Cooperation test
General comfort	Cooperation test

Table 3 Overview of unique features that differ between the HoloLens 2 and Quest Pro.

The results should allow to describe design potentials for future game design for MR in general. When combined with the context exploration this can be used as input in the design process of building a game for ABI motor rehabilitation that will later on be used to test the experiences of ABI patients. Furthermore, the results can be used to explain later results of the test with ABI patients by linking results back to specific features defined in this chapter.

5.1 Method

5.1.1 Participants

As the goal is to assess the differentiating features of the MR headsets, the tests are done with healthy participants to receive more detailed feedback. Participants are gathered through the researcher's network and at the office building The Alchemist at which HoloMoves is located. The only exclusion criterium is that participants should have no major previous experience with XR that could influence the study.

5.1.2 Materials

FoV Test

The primary goal of the FoV test is to create an understanding of how the size of the FoV influences the general experience of participants when moving around in a space while wearing a MR headset. This includes the subjective experience and the effectiveness of the task. The secondary goal is to test how the spatial awareness of the participant is affected by the size of the FoV. This entails e.g., the search behavior of the participant, and understanding where (virtual) objects are in the space.

A simple game was built in Unity. The game consists of two rounds that follow each other automatically. The first round consists of 10 balls, 9 pink and one blue, that are placed in the room surrounding the participant. The participant has to find and touch them to let them disappear, ending with the blue ball. Afterwards, the second round starts which consists of a series where 2 balls, 1 pink and 1 blue, are in the room at the same time which have to be found and popped, again first pink and then blue. The balls are placed in such a way that they are close or outside of the peripheral view of the user. By letting the user end with the blue ball, the placement of the balls relative of the user is controlled.

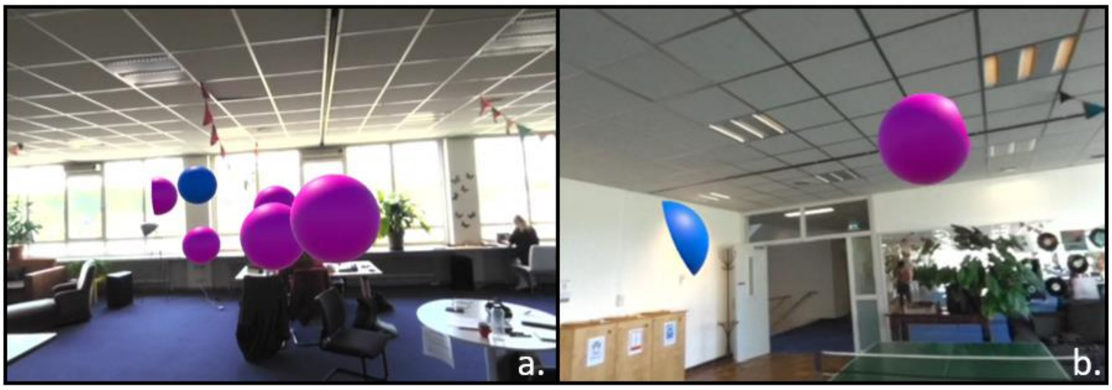


Figure 6 FoV test with limited FoV size (condition 2) where a. shows round 1 of the test and b. shows round 2 of the test.

For the FoV test only the Quest Pro will be used. This is done to be able to influence the FoV size while keeping all other factors the same. By doing this, the influence of the FoV size on the experience of participants can be measured separately from the other unique features of the headsets as seen in Table 1.

This resulted in 2 conditions: condition 1 consists of the full FoV of the Quest Pro whereas condition 2 consists of a limited FoV of a comparable size as the HoloLens 2. Like the HoloLens 2, the user can see the rest of the world through passthrough outside of the FoV, but virtual content is only shown in the restricted FoV. To restrict the FoV, a dot product of 0,93 is used which equals to an angle of 21,5° and therefore a total FoV of 43°. Each participant will test both conditions in random order.

Cooperation test

The primary goal of the Cooperation test is to create an understanding of how the ability to have direct eye contact influences the experience and communication between people who have to perform a joint task. This also includes the ability to read the emotional state of a person wearing different MR headsets as the context exploration showed this was an important element of rehabilitation. The secondary goal is to get an understanding of how different characteristics of the headsets influence the experience of the user, such as how the opacity of virtual content influences the experience of the user, if users experience different levels of simulation sickness, and general comfort of the two headsets.

To be able to test these characteristics, both the HoloLens 2 and the Quest Pro will be used. As task for this test, a stripped-down version of the game Keep Talking and Nobody Explodes was recreated in Unity (Keep Talking and Nobody Explodes, n.d.), see Figure 7. During the task two participants have to work together to dismantle a virtual bomb by solving puzzles. One of the participants gets a MR headset and can see and interact with the virtual bomb. The other participant gets a set of instructions from the instructions manual of Keep Talking and Nobody Explodes, which is required to be able to solve the puzzles, see Appendix 12.2.4 for the manual that is used in the test. The goal is to work together and to finish the puzzles without losing all their lives and before the time is finished.

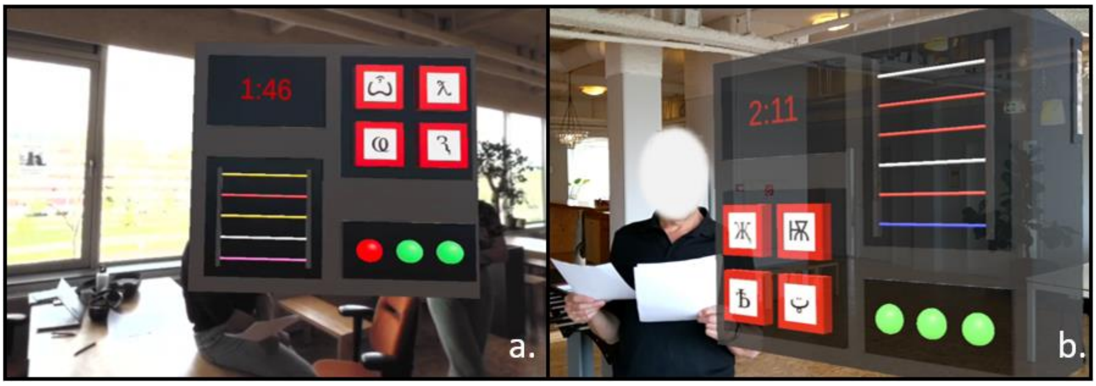


Figure 7 The Cooperation test condition 2a where a. shows level 1 on the Quest Pro and b. shows level 2 on the HoloLens 2.

Two levels were made with the same type of tasks, rules, and difficulty so both headsets can be tested without doing exactly the same puzzles twice. The order of testing the headsets and the levels will be randomized to control for a learning effect, resulting in four conditions, see Table 4. Each set of participants will test one of the conditions where the roles of the participants stay the same throughout the test. The conditions are randomly assigned to a set of participants.

Condition	First MR system	First Level	Second MR system	Second Level
1a	HoloLens 2	Level 1	Quest Pro	Level 2
1b	HoloLens 2	Level 2	Quest Pro	Level 1
2a	Quest Pro	Level 1	HoloLens 2	Level 2
2b	Quest Pro	Level 2	HoloLens 2	Level 1

Table 4 Overview of the conditions tested in the Cooperation test.

5.1.3 Procedure

All participants will be informed on the study and are asked to sign a consent form before partaking in the study.

A within-subject setup is applied to each test individually, this allows the possibility to compare different conditions within a test on the same participant. Participants can either partake in only one of the Design exploration tests, or in both. In both tests the order of conditions is randomized to account for the possibility of practice- and/or fatigue effect.

The tests will be done at four different locations to be able to gather and reach as many people as possible to participate in the study, see Table 5. In addition, it allows to gather information on how different locations and light sources influence the performance of the headsets. Each location has enough moving space to be able to perform the tests, in addition objects will be removed if needed to ensure the safety of the participants.

Location	Space	Light
The Alchemist	Small kitchen 1st floor	No windows, TL lights
The Alchemist	Spacious canteen 1st floor	Many windows & direct sun
The Alchemist	Spacious canteen 2nd floor	Many windows & indirect sun
UT Campus	Living room	Windows & indirect sun

Table 5 Overview of the test locations of the Design exploration tests.

Before the tests, the participants will be informed about the task they are about to participate in (either the FoV test or the Cooperation test) and its goal without telling the difference between conditions. Next the researcher helps the participant put on the MR headset and adjust it, so it sits correctly and comfortably. The participant is then instructed which condition they should select within the headset and start with the task.

After finishing the first task, the participant is asked to answer a set of questions. After finishing filling out the questions, the same steps of the first condition are repeated for the second condition. After the second condition they get the same set of questions as the first condition with some additional open questions to compare the conditions. In total, the FoV test generally will take 15-20 minutes per participant and the Cooperation test will take about 30 minutes per participant.

5.1.4 Measures

A convergent mixed methods research design is applied to combine qualitative and quantitative measurements (Meissner et al., 2013).

To measure the experiences of participants during the FoV and Cooperation test, a 7-point Likert scale is used where participants have to tick a box on how much they agree with the statement (1 being not at all, 7 being very much). The FoV test consists of 15 statements, the Cooperation test of 16 statements for the headset wearer and 9 statements for the instruction giver. In addition, the headset wearer of the Cooperation test also gets 8 statements on simulation sickness where the participant has to give a score (1-4) of how much they experienced the sensation (e.g., dizziness, headache), see Appendix 12.2 for the list of statements. The statements and scoring system of the simulation sickness are based on previous work by J. Lohman on reducing cybersickness (Lohman, 2021).

To be able to explain and contextualize the quantitative findings gathered through the Likert scale questions, a set of open questions are asked at the end of each test. The participants of the FoV test and the headset wearer of the Cooperation test get 6 open questions, the instruction giver of the Cooperation test gets 5 open questions.

Last, to get a better understanding of how the experiences of participants match with their observed behavior, video recordings from the perspective of the headset are made. Observations from the recordings on the behavior will be written down and summarized, and the completion time of the task will be measured.

5.1.5 Data analysis

To analyze the difference in responses in the Likert scale statements, the paired Wilcoxon test will be applied to each question to test if there is a significant difference between conditions. The Wilcoxon test is a within-subject analysis that assesses the change of an ordinal outcome across two within-subject observations or two time points (Heidel, 2016). In addition, it is also employed when a violation of the statistical assumption of normality of difference in scores for a repeated-measures t-test is violated. As the Wilcoxon test will be applied to each question, a multiple testing correction should be done to reduce the number of false positives. The raw p values will be adjusted according to the FDR method as a multiple testing correction. The FDR method was chosen over the Bonferroni method as the FDR method reduces false positive while also minimizing false negatives, whereas the Bonferroni method can be quite conservative which can increase the false negative rate (Jafari & Ansari-Pour, 2019).

The open questions will be analyzed by searching for general themes in the answers which will be summarized per question. In addition, they will be compared to the results of the Likert scale questions to be able to provide context to the Likert scale questions.

Similarly, the recordings will be analyzed by observing the behavior shown and looking for general themes that can be seen. The themes of each condition will be compared with the themes of the other conditions. In addition, the results will be compared to that of the Likert scale questions and the open questions to compare the experienced and observed behavior.

To compare the completion times of the different conditions of the FoV test, a paired T-test or the paired Wilcoxon test will be used, depending on if the assumption of normality is met or not.

5.1.5 Ethics

The research plan for the Design exploration tests got judged and approved by the ethics committee CIS of the University of Twente.

5.2 Results

5.2.1 Participants

In total 20 healthy participants were included of whom 8 took part in both tests, 6 took part only in the FoV test, and 6 took part only in the Cooperation test.

The FoV test included a total 14 participants (5 women and 9 men). The participants were between the ages of 14 and 61 ($M = 30.5$, $sd = 15.5$).

The Cooperation test included a total of 14 participants, 7 as MR headset wearers (4 women and 3 men) and 7 as instruction givers (2 women and 5 men). The headset wearers were between the ages of 14 and 44 ($M = 24.0$, $sd = 8.8$). The instruction givers were between the ages of 19 and 49 ($M = 28.9$, $sd = 11.6$).

5.2.2 FoV Test

Completion time

As the assumption of normality was not met, the paired Wilcoxon test was employed. The completion time of the limited FoV was between the 40 seconds and 144 seconds with a median of 59.5 seconds and an IQR of 30 seconds. For the full FoV the completion times were between the 27 seconds and 55 seconds with a median of 38 seconds and an IQR of 19.2 seconds. The paired Wilcoxon showed a raw p value of 0.00763 meaning that $p < a = 0.05$ and an effect size of 0.782. So, a significant difference in completion time of the limited FoV and full FoV was found.

Likert scale questions

First the median of each question of the two conditions, a limited FoV and a full FoV, were calculated together with their IQR, see Figure 8. Because the test is on the experience of people, the variability between participants can be quite large. To see if there were any significant differences between conditions, the paired Wilcoxon test was applied to each question followed by a FDR p value adjustment, see Table 6.

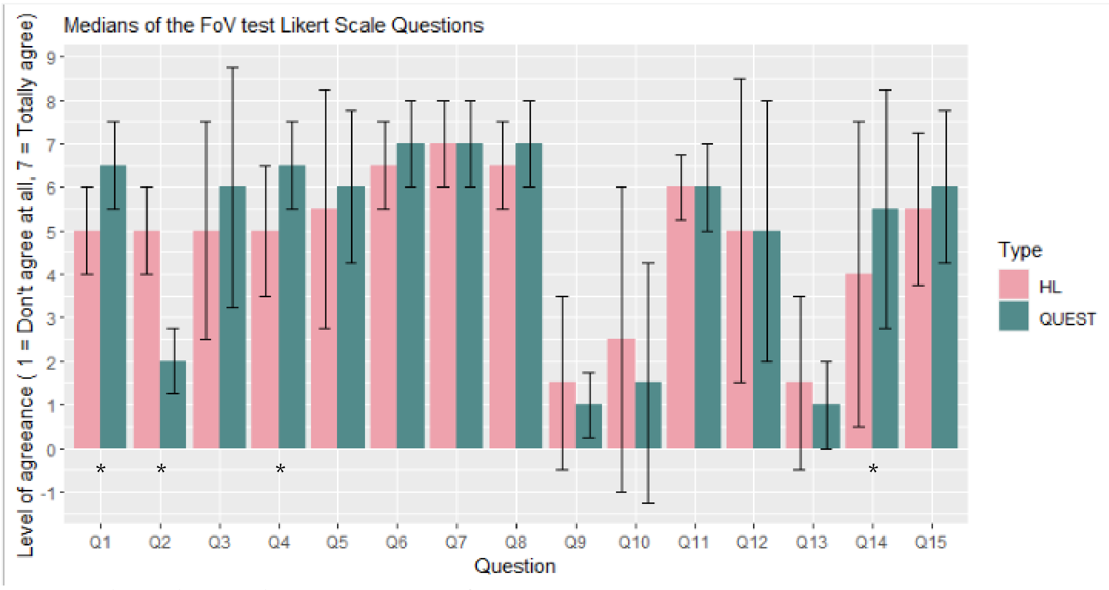


Figure 8 The medians and IQRs per question for FoV test.

Question	Limited FoV median	Full FoV median	Adjusted P value	Effect size
Q1*	**5.00 (1.00)**	**6.50 (1.00)**	**0.0473**	**0.741**
Q2*	**5.00 (1.00)**	**2.00 (0.75)**	**0.0144**	**0.891**
Q3	5.00 (2.50)	6.00 (2.75)	0.110	0.559
Q4*	**5.00 (1.50)**	**6.50 (1.00)**	**0.0409**	**0.812**
Q5	5.50 (2.75)	6.00 (1.75)	0.303	0.389
Q6	6.50 (1.00)	7.00 (1.00)	0.303	0.378
Q7	7.00 (1.00)	7.00 (1.00)	0.766	0.120
Q8	6.50 (1.00)	7.00 (1.00)	0.641	0.139
Q9	1.50 (2.00)	1.00 (0.75)	0.303	0.471
Q10	2.50 (3.50)	1.50 (2.75)	0.468	0.299
Q11	6.00 (0.75)	6.00 (1.00)	0.530	0.267
Q12	5.00 (3.50)	5.00 (3.00)	0.303	0.301
Q13	1.50 (2.00)	1.00 (1.00)	0.641	0.207
Q14*	**4.00 (3.50)**	**5.50 (2.75)**	**0.0416**	**0.779**
Q15	5.50 (1.75)	6.00 (1.75)	0.413	0.291

Table 6 Results of the paired Wilcoxon test with FDR adjusted P value per question of the FoV test.

From the table it can be concluded that the median scores of questions 1 (I knew if I had found all balls, p = 0.0473), question 2 (I had to search a lot, p = 0.0144), question 4 (I could find the next ball easily, p = 0.0409), and question 14 (it felt like the virtual balls were really in the space around me, p = 0.0416) are significantly different in the two conditions as the p-values are smaller than a = 0.05 combined with all relatively large effect sizes.

The majority of the significant results (Q1, Q2, and Q4) are part of the question regarding spatial awareness (Q1 – Q5). The questions regarding freedom of movement (Q6 – Q10) show no significant differences, the largest difference can be seen in Q9 (I felt restricted in my movements), however, the median in both conditions is still under a 2 meaning for both conditions people disagreed and did not feel restricted. The rest of the general questions (Q11 – Q15) also show for the majority no significant differences except for Q14.

Open questions

The open questions had 5 main topics: preference, feeling of being in control, difficulty of task, realism of virtual content, and general influence of FoV on their experience.

The majority of participants (13 of 14) preferred the larger FoV Some reasons given were that it felt more realistic, insightful, and more freedom in looking around and their movements, in addition some felt less lost and calmer, and didn't have to search as much. The last participant found the conditions comparable and didn't have a preference.

Again, the majority (9 of 14) felt more in control with the larger FoV due to being able to see more making the task easier, clearer, and smoother. However, the other 5 participants did not feel much difference because they were still able to complete the task and did not feel more in control during one of the conditions.

The participants were equally divided (7 of 14) on the topic whether the tasks were comparable in difficulty. Most participants who argued the tasks were equally difficult stated the tasks in essence were the same which was true. The participants who argued they weren't equally difficult stated that the full FoV was easier because they had to search less and could see more.

Again, the participants were equally divided (7 of 14) on the topic of realism. Participants who found them equally realistic thought so because they could see the real world and virtual content at the same time in both conditions. Participants who found the larger FoV more realistic argued this because in the smaller FoV the virtual content was partially cut off.

The FoV influenced each participant quite differently, while some mentioned they felt they could move more freely, another mentioned the FoV did not influence their movements. The most mentioned themes are that a larger FoV creates a calmer experience, a clear overview of the space, and feels more realistic. In contrast, a more limited FoV can create a more chaotic experience, makes it more exciting and difficult which can be beneficial for gameplay, however, another participant also mentioned it made them feel unfairly limited.

5.2.3 Cooperation test

Likert scale questions headset wearer

Again, first the results were explored by looking at the medians and IQRs per question per condition, the HoloLens 2 and the Quest Pro, see Figure 9. Afterwards the paired Wilcoxon test with FDR p-value adjustment was employed to check for significant results. The test showed no significant differences in the medians of the two conditions with a=0,05, see Table 7. It is noteworthy that the IQRs are generally quite large showing a wide variety of opinions of the participants. Q1 – Q7 were on the collaboration during the task while Q8 - Q16 were on the ease of use of the headset.

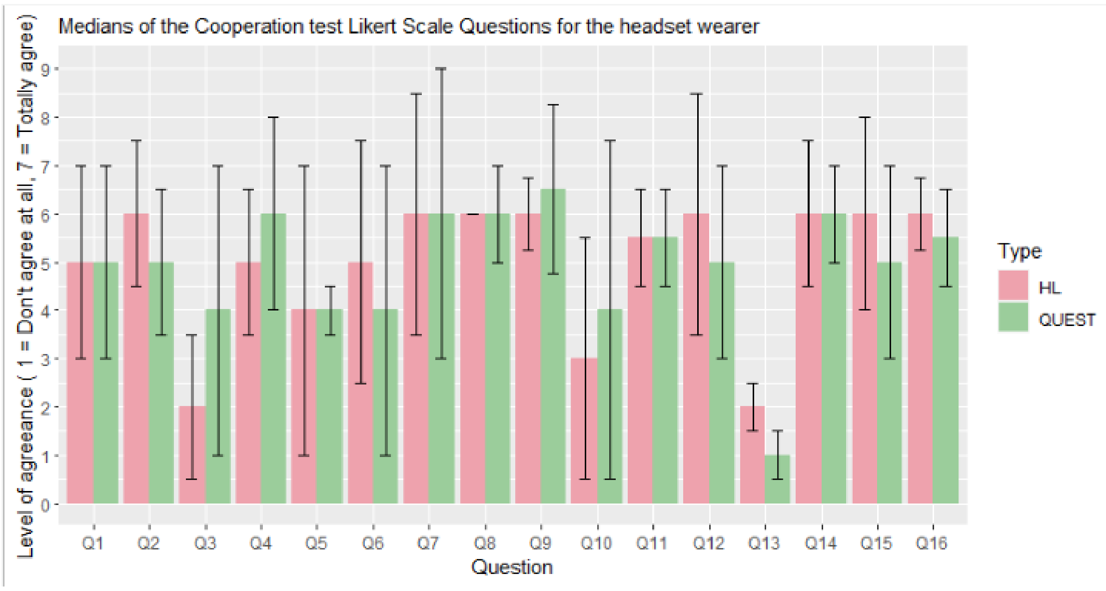


Figure 9 Medians and IQRs per question for the headset wearer in the Cooperation test

Question	HL median	Quest median	Adjusted P Value	Effect size
Q1	5.00 (2.00)	5.00 (2.00)	0.857	0.298
Q2	6.00 (1.50)	5.00 (1.50)	0.857	0.407
Q3	2.00 (1.50)	4.00 (3.00)	0.857	0.196
Q4	5.00 (1.50)	6.00 (2.00)	0.857	0.265
Q5	4.00 (3.00)	4.00 (0.50)	0.887	0.197
Q6	5.00 (2.50)	4.00 (3.00)	0.857	0.407
Q7	6.00 (2.50)	6.00 (2.50)	0.951	0.130
Q8	6.00 (0.00)	6.00 (1.00)	0.857	0.533
Q9	6.00 (0.75)	6.50 (1.75)	0.857	0.280
Q10	3.00 (2.50)	4.00 (3.50)	0.951	0.164
Q11	5.50 (1.00)	5.50 (1.00)	1.00	0.140
Q12	6.00 (2.50)	5.00 (2.00)	0.857	0.355
Q13	2.00 (0.50)	1.00 (0.50)	0.951	0.272
Q14	6.00 (1.50)	6.00 (1.00)	0.857	0.407
Q15	6.00 (2.00)	5.00 (2.00)	0.857	0.296
Q16	6.00 (0.75)	5.50 (1.00)	0.857	0.280

Table 7 Results of the paired Wilcoxon test with FDR adjusted P value per question of the Cooperation test for the headset wearer.

Simulation sickness headset wearer

For the simulation sickness questions, the medians and IQRs were calculated for each question, see Table 8. It can be noted that all responses are between the scores of 1 (not at all) and 2 (a little bit) with question 17.3 (difficulty focusing vision) for the Quest condition being the exception with a median of 4 (strong), though also with the largest IQR of 2.5.

Question	Median HL	Median Quest
Q17.1	1.0 (0.0)	1.0 (0.5)
Q17.2	1.0 (0.0)	2.0 (1.0)
Q17.3	1.0 (1.0)	4.0 (2.5)
Q17.4	1.0 (0.0)	1.0 (0.0)
Q17.5	1.0 (0.0)	1.0 (1.0)
Q17.6	1.0 (0.0)	1.0 (0.0)
Q17.7	1.0 (0.0)	1.0 (0.0)
Q17.8	1.0 (0.0)	1.0 (0.5)

Table 8 Medians and IQRs per question and condition on simulation sickness of the Cooperation test.

Open questions headset wearer

The open questions had 5 main topics: preference, quality of collaboration, feeling of being in control, ability to have eye contact, and general comfort of the headset.

Two participants didn't prefer a headset, 2 participants preferred the Quest Pro, and 3 participants preferred the HoloLens 2. The location of the test had a large influence on the preference of participants. Participants said to prefer the HoloLens 2 because it provided a lighter surrounding, the image was clearer, and was more comfortable. In addition, the Quest Pro generated flickering images in spaces that were for the majority lit by artificial light sources. Participants who preferred the Quest Pro argued it had a clearer image than the HoloLens 2, this was mostly an answer when the test was in a brightly lit room filled with sunlight which made the image on the HoloLens 2 less clear and harder to see. Another argument given was that they were frustrated by the image being cut off in the HoloLens 2 which made it less realistic.

Four Participants experienced better collaboration with the HoloLens 2, 2 participants didn't notice a difference, and 1 participant experienced better collaboration using the Quest Pro. The arguments provided for either headset were mainly based on the order in which they tested a headset, resulting in the second tested headset having a preference because they understood the assignment better. Another argument given for the HoloLens 2 was that they could see the environment and therefore their partner better.

Two participants felt equally in control in both headsets, 2 participants felt more in control in the HoloLens 2, and 3 participants felt more in control in the Quest Pro. For both systems it was argued by participants that it was due to the clearer image, this can most likely be argued by the influence of the surrounding and the lighting as explained in the section on the preference.

There was no clear preference for one of the headsets based on the possibility to have direct eye contact, however, the majority (6 of 7) did explicitly state they enjoyed being able to see the other person. From the perspective of the headset wearer this was possible in both headsets.

The majority of the participants (4 of 7) found the HoloLens 2 more comfortable to wear, 2 participants found the Quest Pro more comfortable, and 1 participant had no preference. The HoloLens 2 was generally experienced as more lightweight, more user friendly to put on, and generally more comfortable feeling on the head. The Quest Pro was preferred because it left space on top for the participants hair to stick out and because it wasn't pressing on the glasses of a participant.

Likert scale questions instruction giver

First the medians and the IQRs were calculated per question to get an overview of the general rating for each question per condition, see Figure 10. To see if any of the questions had a significant difference in the median on the different conditions, the paired Wilcoxon test with a FDR p-value adjustment was applied, see Table 9. There were no significant differences. All questions were on the collaboration during the task.

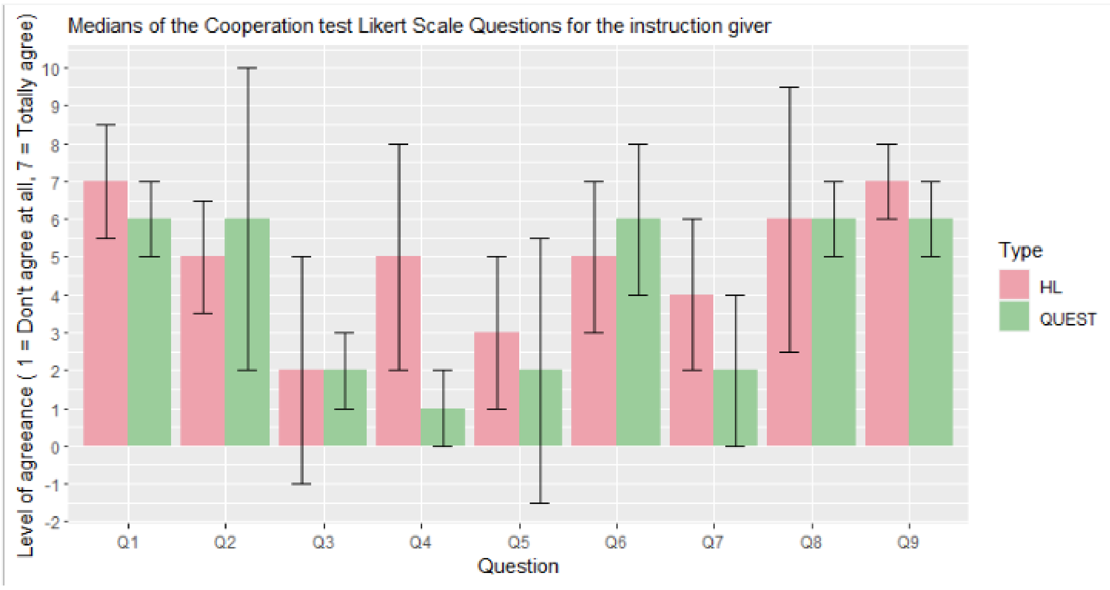


Figure 10 Bar plot of the medians and IQR per question and condition of the Cooperation test for the instruction.

Question	HL median	Quest median	Adjusted P Value	Effect size
Q1	7.00 (1.50)	6.00 (1.00)	1.00	0.0679
Q2	5.00 (1.50)	6.00 (4.00)	1.00	0.135
Q3	2.00 (3.00)	2.00 (1.00)	0.591	0.472
Q4	5.00 (3.00)	1.00 (1.00)	0.450	0.741
Q5	3.00 (2.00)	2.00 (3.50)	1.00	0.679
Q6	5.00 (2.00)	6.00 (2.00)	1.00	0.0337
Q7	4.00 (2.00)	2.00 (2.00)	0.450	0.742
Q8	6.00 (3.50)	6.00 (1.00)	1.00	0.131
Q9	7.00 (1.00)	6.00 (1.00)	1.00	0.0679

Table 9 Results of the paired Wilcoxon test with FDR adjusted P value per question of the Cooperation test for the instruction giver.

Open questions instruction giver

The open questions had 4 main topics: preference, quality of collaboration, ability to have eye contact, and ability to read stress levels.

Four Participants did not prefer one of the headsets and 3 participants preferred the HoloLens 2. The participants who didn't have a preference argued that the experiences were similar to each other and/or that they were mostly focused on providing instructions rather than looking at the headset or the other participant. The participants who preferred the HoloLens 2 argued that they could see more of the other person wearing the headset, they themselves felt more visible, and that the teamwork went more smoothly.

The quality of collaboration was not based on the headset but rather on the order of doing the test, resulting in the second try having better collaboration because the task in general went better.

The majority (6 of 7) said the possibility to have direct eye contact with their partner did not influence the experience. Most participants were focused on providing the instructions resulting in them not looking at their partner. 2 participants also mentioned they were not sure to what extend their partner could see them or had the feeling they were not seen at all. Another response was that if they would have understood the puzzle and task better, they would have liked to look at their partner and it could have been beneficial, this also ties in with the answer of the only participant who did say it influenced the experience. They argued they felt more involved during the task while the HoloLens 2 was used because they could directly look at the other person.

The majority (5 of 7) did not think the type of headset influenced their capability of reading the others stress levels, 1 participant argued they could read the other's stress level better with the HoloLens 2 because they could see the other's face, and 1 participant argued that being able to see less of the other person increased stress they experienced in general. Most participants argued they based the stress levels of the other on their voice rather than on their face.

5.3 Discussion

The goal of this discussion is to tie the results of the different types of measurements and tests together to create a general overview of the findings. As previously mentioned, the focus was on measuring the influence of the individual characteristics of the differences between the HoloLens 2 and the Quest Pro. Due to the small sample size of both tests, there was a large variety in responses resulting in large IQRs in the Likert scale questions. This might have been part of the reason there were only 4 significant results found in the Likert scale questions of the

FoV test and there was no prove of significant results in the Cooperation test. Additionally, there was a significant difference in completion time found in the FoV test.

Of the FoV test, three out of four significant results were questions on the spatial awareness of participants. These questions indicate that participants experienced a harder time finding objects and were less sure where the next object was or if they had found everything in a smaller FoV. The significant difference in completion time, open questions and recordings also confirmed this, participants argued they felt more lost and less calm with a restricted FoV which resulted in more search behavior and walking more circles to find the objects as observed in the video recordings.

A contradiction in participants' responses and observed behavior was on the topic of freedom of movement. Participants argued in the FoV test that they did not feel restricted in their movements by the limited FoV, both in the Likert scale questions as well as in the open questions, however, when analyzing the recordings a difference in movements could be observed. In the limited FoV, the majority of participants were moving more slowly and carefully scanning the room. In the full FoV they were moving more quickly and seemed to be surer in their movements. The difference in experienced and observed behavior could indicate that the size of the FoV influences participants behavior without them being aware of this change.

The last significant result of the FoV test was on how realistic the virtual balls felt. A limited FoV decreased the sense of realism of the virtual content being in the real world. This was also confirmed by the open questions where a number of participants argued that the full FoV made the balls more realistic, the limited FoV was considered less realistic due to the virtual content being cut off.

There were no significant results found in the Likert scale questions of the Cooperation test. This is also reflected in the open questions as people were for the majority equally divided in their preference in headset. One of the most important reasons given to prefer a system was the quality and clarity of the image which was heavily affected by the location of testing. The HoloLens 2 was sensitive to bright natural light which caused the virtual content to be see-through and hard to see in spaces with a lot of windows and natural light. On the contrary, the image of the real world in the Quest Pro can be sensitive to the flickering of light sources depending on the power frequency, meaning that if the setting of the headset is not set to the right geographic area and corresponding power frequency, the entire image will be flickering. The cause of the flickering image was found after the testing had already ended so could not be fixed prior to testing. This influence of light sources caused participants who tested at a location with many windows on a sunny day to prefer the Quest Pro while participants who tested at a location with no windows preferred the HoloLens 2. When the light of the location did not play role in the testing, the poor image quality of the real world in the Quest Pro was the main reason for the majority of the remaining participants to prefer the HoloLens 2. The Quest Pro's representation of the real world is limited due to its camera's resulting in a very grainy representation and poor quality (VRX, 2023a).

The Cooperation test was meant to stimulate participants to work together and test the capabilities of the instruction giver to read the emotional state of their partner. However, participants argued they were mostly focused on the task instead of looking at their partner which was the case for both roles. In the open answers they argued they mostly read the stress levels of their partner through the voice and the tone of their partner rather than looking at their facial expressions. It is therefore likely that the test was not as suitable to test eye contact and the possibility of reading stress through facial expressions as anticipated prior to testing. However, based on the interviews with the therapists as discussed in chapter 4.2.2, it is expected that this is still an important aspect when MR is applied to therapy as they argued looking at the complexion was one of the main methods to judge the emotional state of a patient.

Last, the majority of questions about simulation sickness were rated between a 1 (no symptoms at all) and 2 (a little bit of symptoms). The only exception was the question on having difficulty focusing their vision for the Quest Pro which had a median of 4 (strong symptoms). While this can be related to simulation sickness, it is more likely this is related to the image quality of the Quest Pro itself instead of the image making people feel motion sickness because of all the other low scores. Therefore, there is no indication that simulation sickness is a problem for either the HoloLens 2 or the Quest Pro.

5.4 Implications for Future Game Design

From the results and discussion of the Design exploration tests, implications can be made for general future game design when designing for MR headsets. In addition, some features can help guide the choice of which headset might be more suitable for certain games. While the results might offer some implications, they should be taken with a grain of salt as the sample sizes of both tests were rather small which decreases the generalizability of these results.

5.4.1 FoV and Spatial Awareness

As mentioned, the size of the FoV influences the spatial awareness of participants and perceived realism of the game, especially in regard to the general overview of the game and the location of target objects. This should be taken into consideration when designing a game. When the goal of the game is to increase difficulty in search tasks or increase tension in the game, this feature can be utilized by decreasing the FoV size or to choose a headset with a smaller FoV. However, when this is not the goal it can be more comfortable for users to have a larger FoV to have a better overview of the game, to perceive the game is more realistic, and to not have the size of the FoV be a distraction.

Additionally, while the users did not experience a difference in their freedom of movement, there was an observed difference. For general game design when the focus might be more on general enjoyment of the user, this does not have to have any implications. However, in the case of rehabilitation this can have implications when specific movements are required. However, as these results are based on observations of healthy participants, it is difficult to draw strong conclusions for rehabilitation. A more structural method to measure observed movements will therefore be added to the later test with ABI patients.

5.4.2 Direct Eye Contact with Others

The Cooperation task asked for collaboration between two participants, however, this did not require direct eye contact. The results indicate that for collaboration in general, direct eye contact is not needed and that participants can judge the other's emotional state based on the tone and voice of their partner. However, based on the context exploration this is an element that is relevant during rehabilitation as the therapists argued they look at the patient's complexion and gaze to judge if they need to intervene or not. Therefore, more space for direct eye contact will be made in the game design used in the ABI experience test which will allow to test this feature and its importance during rehabilitation in more depth.

5.4.3 Clarity of Virtual Content

While the Quest Pro shows high quality virtual content, the participants found the image of the real world lacking which resulted in being one of the main reasons to prefer the HoloLens 2.

Therefore, when the focus is on interacting with the real world, the HoloLens 2 is likely a more suitable headset. However, when the focus is on virtual content, the Quest Pro shows higher quality images and is more suited for this purpose. Still in the game design it is important to be aware of the poor camera quality of the Quest Pro as it might be a disturbance to users.

5.4.4 Simulation Sickness

The results on simulation sickness show no indication for either headset to cause simulation sickness. While still an important feature to take into account when designing a game, there is no direct indication that either headset should be denied when this is a concern.

5.4.5 General Comfort

The HoloLens 2 was perceived as slightly more comfortable to wear as it was experienced as more lightweight. However, as there were no major differences, the general comfort does not have to dictate which headset is better for employment.

On the contrary, the Cooperation test indicated the importance of the test location and its light source as this is a big influence on the experience and preference of participants. When using the HoloLens 2, and most likely optical see-through in general, the virtual content is sensitive to light meaning that colors can be altered, and objects can be hard to see. It is therefore important to test a game under numerous light conditions and locations to be sure the quality of the game is robust enough. Furthermore, as the image of the Quest Pro is recorded through cameras, it is sensitive to the power frequency of light sources. The headset should therefore be set to the right geographic area, though this is mostly important for the end user rather than for the game design.

6. Game Design for ABI Rehabilitation

The previous chapter provided greater insight into which elements of MR headsets potentially influence the experience of users and in what way. This information can be used for game design in general, however, does not answer how the experience of ABI patients might be influenced, especially in the setting of rehabilitation. Therefore, this chapter will focus on designing a game that can be used to test the experience of ABI patients when MR is used for motor rehabilitation, while taking the results of the previous chapter and the answers of the context exploration into account.

The game is inspired by the game Tableball made by HoloMoves, as it was designed for upper limb motor rehabilitation for ABI patients. The basics are used as basis; however, an altered version will be made to fit the requirements for the ABI experience test, e.g., be applicable for multiple platforms, the game used for testing will therefore be called Multi-Platform Tableball (MPT).

The basis of the MPT consists of a virtual pocket that is placed on the table, and virtual billiard balls located on the table in front of the participant. The goal of the game is to play the billiard balls into the pocket by pushing the balls into the right direction. This was the starting point of designing MPT further, the game went through a few iterations where the design was done by me and the implementation was done by Yerio Janssen, Trainee Jr. Developer at HoloMoves.

6.1 Iterative Design Process of Multi-Platform Tableball

Based on the results of the Design exploration tests, several adjustments have been made to MPT.

First, an important feature to incorporate is to have virtual objects outside of the peripheral view to be able to test the difference in FoV size and the spatial awareness of participants, as these elements showed significant differences in the FoV test. These differences were seen when participants were walking around to find objects, however, as participants will be seated in the ABI experience test this has to be done in a different manner. Therefore, balls are placed in front and next to the user in the air, in addition to being placed on the table, so that participants have to search for the balls. To get the ball from the air onto the table the participant has to touch the ball which makes it 'jump' to the table in front of the user so they can continue playing it into the pocket.

Next, I want to have more control over the search behavior of participants and be able to measure the time it takes to find a ball. To do this, instead of having all the balls around the participant at the same time, the balls will only appear one at a time for which a cue will be given to find the specific ball. From it can be measured how long it takes the participant to find the ball since the cue was given. In addition, the areas in which a ball can appear are predefined and color-coded, see Figure 11. For example, the pink ball will always appear in a certain spot. As a participant will play the same game multiple times, the order in which the balls appear is randomized to control for learning effect.

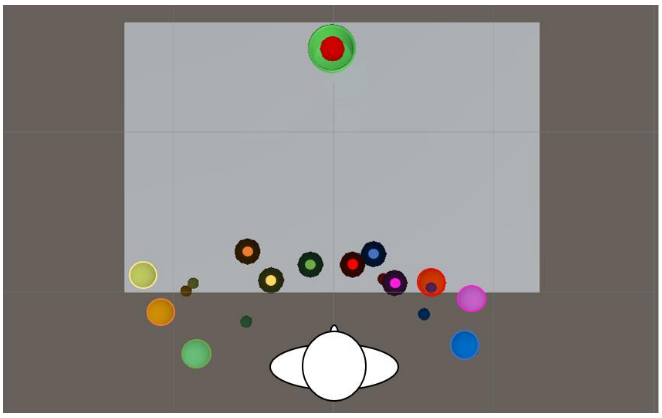


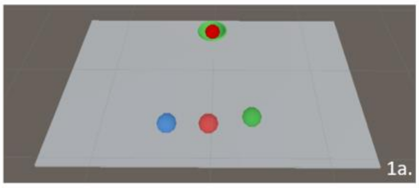
Figure 11 View from above of the redefined areas of the balls in the game for the ABI experience test. The fully colored circles indicate the area in the air, the dotted circles indicate the area the ball will fall on the table.

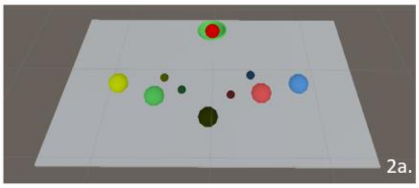
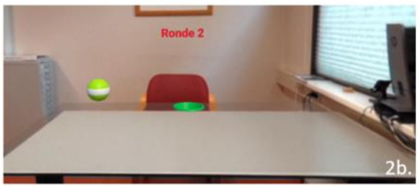
While the search behavior is now accounted for by having the balls placed individually around the participant, it means participants have to move their arm to touch the balls. However, because the target group consists of ABI patients who experience various levels of upper limb problems, it restricts the sample size that can participate in the test. To increase the sample size, the interaction type with the balls in the air is changed from having to touch the ball, to having to look directly at the ball. By looking directly at the ball for 1 second the ball is activated and will 'jump' to the table. From here the interaction stayed the same where the participant has to move their arm over the table and move the ball towards the pocket.

Last, the game needs an element where the participant has to interact with the therapist or researcher, depending on who guides the test. In addition, the game needs more of a buildup so the goal and the required interactions are easier to understand for the participant as these might not be self-evident. These requirements are combined by adding two stages prior to the final stage. Each stage will be accompanied by a set of instructions provided by the therapist or researcher, see Figure 12. The first stage is meant as an introductory stage where the balls are located on the table in front of the participant, and they only have to touch it to play it into the pocket. After playing three balls the second stage will start, which is indicated on the screen and by the therapist/researcher providing the next instructions. In this stage the balls are located in the air but still in front of the participant so they can easily see them. The participant has to look at the ball to let it drop to the table from where they can play it into the pocket. After playing four balls the third and final stage will begin. The final stage consists of the previously explained design, the participant gets a cue of which ball to find which is located left or right of the participant. They have to play 6 balls after which the game is finished and returns to the home screen.

This game is made to be tested on both the HoloLens 2 and the Quest Pro. However, even though MPT is made compatible for both headsets, it is expected to be more suitable for the HoloLens 2 because it allows for easier interaction between the patient and another person according to the results of the Cooperation test, which is an important element in the game. In addition, the original Tableball on which the game is based was designed for the HoloLens 2 meaning the game might be more targeted towards the HoloLens 2. To be able to make a fair comparison between the headsets and their unique qualities, an extra version, or redesign, of MPT (reMPT) is made that is better suited for the Quest Pro. By making this redesign, the ABI experience test will eventually consist of three conditions: MPT tested on the HoloLens 2 (HL), MPT tested on the Quest Pro (QP), and reMPT tested on the Quest Pro (reQP). As the redesign will be using features that are not supported by the HoloLens 2, this version cannot be tested on the HoloLens 2 but only on the Quest Pro.

<table>
<tr><td>Stage 1

Balls start one at a time on the table in front of the patient</td><td></td><td></td></tr>
<tr><td>Stage 2

Balls start one at a time in in the air above the table in front of the patient</td><td></td><td></td></tr>
<tr><td>Stage 3

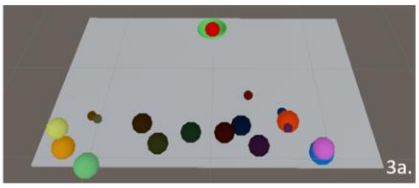
Balls start one at a time in the air around the patient</td><td></td><td></td></tr>
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Figure 12 Scheme of the stages of a test, a. showing the locations of the balls for each stage as build in Unity, b. showing what it looks like through the Quest Pro.

6.2 Redesign for Characteristics of the Quest Pro

In the redesign the goal is to use the unique qualities of the Quest Pro to make the experience better suited for the headset. In addition, the findings of the previous chapter are used as input to improve the experience.

The Cooperation test showed that a major drawback of the Quest Pro was its poor camera quality resulting in the real world looking blurry and grainy, while the virtual content was in focus. This is a flaw that is caused by the hardware of the system rather than a design flaw or software based, meaning this is not something that can be fixed. However, it can be manipulated to draw the attention away from the grainy looking real world and put the attention on the virtual content as this is one of its strong qualities.

A unique characteristic of the Quest Pro, compared to the HoloLens 2, is its capability of manipulating the real world, think of passthrough styles such as applying colored filters, adjusting the lighting, or selective passthrough (Oculus VR, 2021). This is a unique characteristic of video see-through mixed reality in general as it uses cameras and lenses/screens to view the real world. This means it is a real time recording that can be manipulated. Contrary, with optical see-through mixed reality the participant can see the real world directly and therefore doesn't allow for such manipulations.

This characteristic can be used to put the attention on the virtual content and away from the real world, without removing the real world completely and still keep this key feature of mixed reality. As the game Tableball is inspired by billiards, I decided to stay in the same theme and take inspiration from the game. To draw the attention away from the background, the background is darkened as if covered by shadows. At the same time, a virtual light source is placed above of the playing field to illuminate the table. By doing so, the attention is focused on the playing field, away from the blurry background, which is unique to the Quest Pro, see Figure 13.

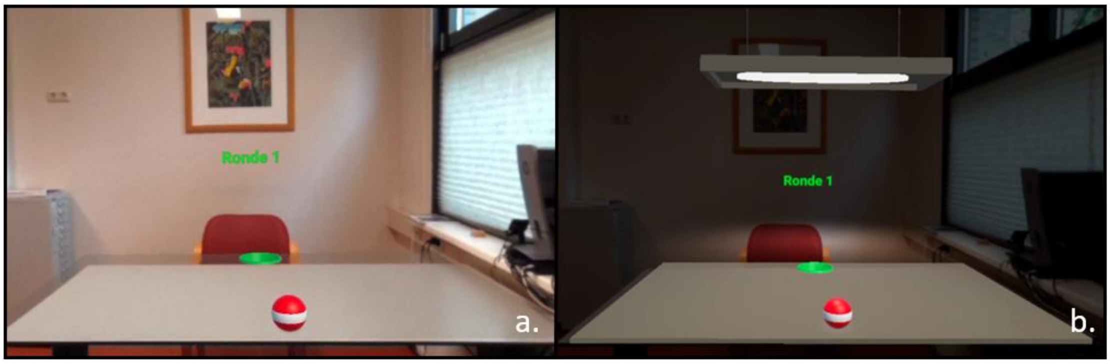

Figure 13 comparison of the MPT as seen through the Quest Pro (a.) and reMPT (b.).

A possible additional benefit could be that by putting the focus on the virtual content, and therefore the task, the focus of the patients could be heightened. According to previous playtests of Tableball carried out by HoloMoves, the application is often used during group therapy leading to more external stimuli. This leads to patients being more easily distracted during their therapy. By darkening the background and putting the focus on the task, it could be beneficial for the task performance of the patient. Even though the levels of focus or distraction were not measured during the Design exploration tests, questions on these topics will be added to the ABI experience test as further explained in the next chapter.

7. The Experience of ABI Patients with Mixed Reality

The Design exploration tests already showed interesting results on the experience of healthy participants with MR and how individual features can influence this experience. These findings were able to provide general advice on how these features might be utilized in game design, which was also shown in the previous chapter. However, the results still leave the question on how these features might influence the motor rehabilitation experience as the tests were done with healthy participants rather than with ABI patients. So, the question on how ABI patients and their therapists experience different forms of MR, and their individual features remains. Therefore, the goal of the ABI experience test is to answer the following main research question:

How do the differentiating features of optical see-through and video see-through differently affect the experience of motor rehabilitation of ABI patients from the perspective of the patient and the therapist?

To make the question more manageable it's broke up in a set of sub questions based on the literature, the context exploration, and the Design exploration tests.

1. *How do patients experience the different FoV sizes of the HoloLens 2 and the Quest Pro?*
2. *What is de difference in the spatial awareness of the patient when using the HoloLens 2 and the Meta Quest Pro?*
3. *How do patients and therapists experience the difference in the possibility of having direct eye contact when using the HoloLens 2 and the Quest Pro?*
4. *How do patients experience the different qualities of image, both virtual content and the real world, between the HoloLens 2 and Quest Pro?*
5. *What is the difference in experienced simulation sickness between the HoloLens 2 and the Quest Pro?*

7.1 Method

7.1.1 Participants

Participants are gathered at rehabilitation center Roessingh with the help of their therapists. The inclusion criteria are that the participant has to be a patient at Roessingh, has to have experienced an ABI, and is receiving upper limb rehabilitation. People who are majorly cognitively affected and/or unable to communicate will be excluded. The aim is to gather approximately 15 patients and 2 therapists.

7.1.2 Experimental Design

Similar to the Design exploration tests, a convergent mixed methods research design is applied to combine qualitative and quantitative measurements (Meissner et al., 2013). Furthermore, a within-subject setup is used. Each participant will test 3 conditions: HoloLens 2 + MPT (HL), Quest Pro + MPT (QP), and Quest Pro + reMPT (reQP). The order of testing the conditions will be randomized to take the effect the conditions might have on each other and the possibility of a learning effect into account.

Setting

The test will take place at an office located at rehabilitation center Roessingh. Each participant will get tested at the same location so the environment will not be a factor influencing the results, as the Design exploration tests showed it played a big role in the experience. Similarly, the light condition for both headsets are checked at the location prior to testing to check that there is no evident difference for the headsets so that none of the headsets will have greater benefits. As there was no evidence for light influencing the headsets at the planned location, no further actions were taken.

Procedure

In the Design exploration tests, the tests were done while standing to increase the influence of spatial awareness of patients that might be altered due to the headset**.** However, due to safety considerations the test with ABI patients is done while sitting down. The game was also designed to facilitate this requirement.

The patient will first be fully informed on the study and the goal of the test, accompanied by the information letter and consent form. Next, some demographics questions will be asked, as will be further described in the measures section, after which the test will start with one of the three conditions which are assigned in random order. Each condition will take approximately 2 – 5 minutes. After each condition, the participant will be asked to answer a set of questions. At the end of all three conditions the participant will be asked a set of final questions. The complete test will take approximately 40 minutes.

7.1.3 Measures

Likert Scale and open questions

The Design exploration tests showed that the Likert scale questions in combination with open questions was a successful measuring tool to question the experience of the participants. The open answers were able to explain some of the significant as well as the non-significant results. Because of this, these tools are also used in the ABI experience test. The set of statements for the ABI experience test consists of statements that showed relevant results in the Design exploration tests, combined with additional statements suited for the specific set of participants and the test. This resulted in a set of 7 demographics questions, 5 open questions, and 25 Likert scale questions on the experience with the following main topics: spatial awareness (Q1 – Q4), freedom of movement (Q5 – Q7), safety (Q9 – Q11), quality of the image (Q12 – Q17), experienced focus (Q18 – Q19), comfort of the headset (Q20 – Q23), and simulation sickness (Q24 – Q25), see Appendix 12.3 for the complete questionnaire that is used.

The demographics questions are asked at the beginning of the test while the open questions are only asked at the end. The Likert scale questions are asked after testing each condition as described in the procedure section.

Behavioral Coding Scheme

The Design exploration tests also showed that the behavioral observations were useful for explaining results. These observations were used to construct a behavioral coding scheme that will be used to annotate behavior in the ABI experience test, see Table 10. This will allow for the qualitative observations to be quantified and afterwards be analyzed for significant differences between conditions. By basing it on the videos, a data-driven approach was taken to develop a coding manual. The frequency of a behavior type will be counted and analyzed through a gold standard approach. Here the researcher will serve as the master coder while a reliability coder will annotate a subset, 20% as this is the standard, which is used for the inter-rater reliability test (Syed & Nelson, 2015).

In the Design exploration tests participants walked a lot of circles while searching for balls. However, because the ABI experience test is seated, participants will not be able to show this type of behavior. It is anticipated that instead of making more circles with a smaller FoV, participants will instead look more left to right and up and down to search for the balls.

	Behavior Type	Description
1.	Checking in	Looking at researcher/therapist to check in or receive instructions
2.	Calm scanning	Slowly looking around the space searching for the next ball
3.	Rushed scanning	Quickly looking around the space and/or switching sides quickly
4.	Change scanning speed	Switch in speed in which they are searching, from calm scanning to rushed scanning or from rushed scanning to calm scanning
5.	Horizontal scanning switch	Switching to the different side to search (from left side to right side or right side to left side)
6.	Vertical scanning switch	Looking up or down to search
7.	Direct find	Directly looking towards the target without having to search
8.	Distraction external stimuli	Looking up to the room, checking the environment instead of focusing on the task
9.	Calm ball interaction	Calmly waiting for the ball to move when it's in the air, a single arm movement to play the ball in a controlled manner
10.	Impatient ball interaction	Making numerous/quick head movements to make the ball drop and/or trying to push the ball from the air/on the table to make it move, trying to play the ball multiple times when it's on the table or already rolling

Table 10 Behavioral coding scheme used to annotate the behavior of ABI patients.

Logged information headset

Last, the Design exploration tests showed there were significant differences in task completion times between the limited FoV and full FoV conditions in the FoV test. Therefore, the completion time of the task in total, the time it takes to get the cue to find an object and to find the object, and if the ball was played into the pocket successfully will be logged for each participant.

7.1.4 Analysis

Likert scale questions

As the sample size is relatively small, it is expected that the spread in answers will be quite large, which was also seen in the Design exploration tests. The FoV test showed a slightly smaller spread in answers with more usable results compared to the Cooperation test which had a very large spread in answers. As it is expected that this was partially due to the sample size, the cut off for a statistical analysis will be $n = 10$ with the expectation that when $n < 10$ the statistical power will be too little to provide meaningful results.

In the case $n \geq 10$, a statistical analysis will be employed. Because this test consists of three conditions, the Friedman's test will be used as it is suitable to compare three or more observations on an ordinal outcome across time or within subjects. Due to the small sample size of this research, the data is expected not to be normally distributed resulting in a non-parametric analysis to be the best fit. Afterwards, the paired Conover's test will be used as post-hoc test to distinguish between which conditions significant differences is found.

In the case of $n < 10$, a descriptive analysis will be applied to be able to interpret the gathered data. This will be done through visualizing the median scores, as it the data is expected not to be normally distributed, accompanied by the spread of the results.

Open ended questions

Similarly, to the Design exploration tests, the open answers will be analyzed for general themes and trends in the answers. These general themes will be summarized per question and can help provide context to the quantitative data.

Behavioral coding scheme

For the behavioral coding scheme, a similar approach as the Likert scale questions is taken. When $n \geq 10$, the Friedman's test will be used to test for the difference in behavior type frequency between conditions as it is also suitable for continuous data. This will again be combined with the paired Conover's test as post-hoc test. When $n < 10$, a descriptive analysis will be done to interpret the results.

To test the objectivity of the behavioral coding scheme, an inter-rater reliability test will be done. An additional coder will annotate 20% of the set of videos using the behavioral coding scheme. Afterwards, the percentage of agreement will be calculated by counting the behavior types that have exactly the same frequency for the researcher and the additional coder and dividing that number by the total number of behavior types and multiplying with 100 to get a percentage (Syed & Nelson, 2015).

Logged information

Like the Likert scale questions and the behavioral coding scheme, depending on the final sample size the completion times will either be tested through the Friedman's test or in a descriptive manner.

7.1.5 Ethics

The test was judged and approved by the Scientific Council of Roessingh. Furthermore, this study got approved by the ethics committee CIS of the University of Twente and did not require further consult. Last, it got checked for WMO (medical scientific research) accreditation and was judged not to be a medical study so no further action was needed.

7.2 Results

7.2.1 Participants

Thirteen ABI patients were approached of whom 9 participated in the test. Two participants (1 woman and 1 man) dropped out after finishing the first condition, one of them had, as a result of their ABI, visual problems already prior to the test which got slightly worse after taking off the headset, so the test got stopped; the other patient had an aversion to technology and did not want to continue after the first condition. This resulted in 7 participants (2 women and 5 men) trying all three conditions. The participants were between the ages of 40 and 78 ($M = 62.6$, $sd = 11.0$). All participants suffered a stroke except for one who suffered a Cavernoma in their brainstem. The incidents happened between the 2 and 17 weeks ago at the moment of testing ($M = 7.9$, $sd = 5.3$).

Due to technical problems with the headsets, not all participants were able to finish each condition which influenced the measurements. Table 11 shows which tests were finished, and which measurements were taken for each participant. Even though some participants were unable to finish a condition, they spend enough time (a minimum of 2 minutes, based on previous playtests performed by HoloMoves) testing the condition to form an opinion on their experience and answer the Likert scale question, this is the case for the p1, p2, and p6 for the HL condition, and for p7 for the QP condition. Similarly, this was the case for analyzing the behavior based on the videos for p1 and p2 for the HL condition.

	Finished HL	Finished QP	Finished ReQP	Video HL	Video QP	Video reQP	Times HL	Times QP	Times reQP	Likert HL	Likert QP	Likert reQP
P1		X	X	X	X	X		X	X	X	X	X
P2		X	X	XS	X	X		X	X	X	X	X
P3	X	X	X	X	X	X	X	X	X	X	X	X
P4*	X			X			X			X		
P5	X	X	X	X	X	X	X	X	X	X	X	X
P6		X	X		X	X		X	X	X	X	X
P7			X		X	X			X		X	X
P8*			X			X			X			X
P9	X	X	X	X	X	X	X	X	X	X	X	X

Table 11 Overview of tests finished, and data gathered per participant. The participants with the stars (*) are the participants who dropped out after the first test.

Furthermore, 2 healthcare providers (1 rehabilitation doctor and 1 physical therapist) were included. The rehabilitation doctor was included during the test of one of the ABI patients who dropped out so was not able to fill out the Likert scale questions on the different conditions, however, was able to provide feedback on the different headsets. The physical therapist was included during a fully completed test and was able to fill out the Likert scale questions and provide additional feedback.

7.2.2 Likert Scale Questions ABI Patients

For the Likert scale questions, 6 participants were included in the analysis (p1, p2, p3, p5, p6, p9). Because the final number of included participants was smaller than 10, a descriptive analysis was done so the medians and the related IQR per question per condition were visually explored. To make it more orderly the questions were split in two and represented in two figures. Figure 14 shows medians of the questions on spatial awareness (Q1 – Q4), freedom of movement (Q5 – Q7), and safety (Q9 – Q11), while Figure 15 shows the medians of the questions on the quality of the image (Q12 – Q17), experienced focus (Q18 – Q19), comfort of the headset (Q20 – Q23), and simulation sickness (Q24 – Q25). A total overview of the medians and IQRs per question per condition can be seen in Table 12.

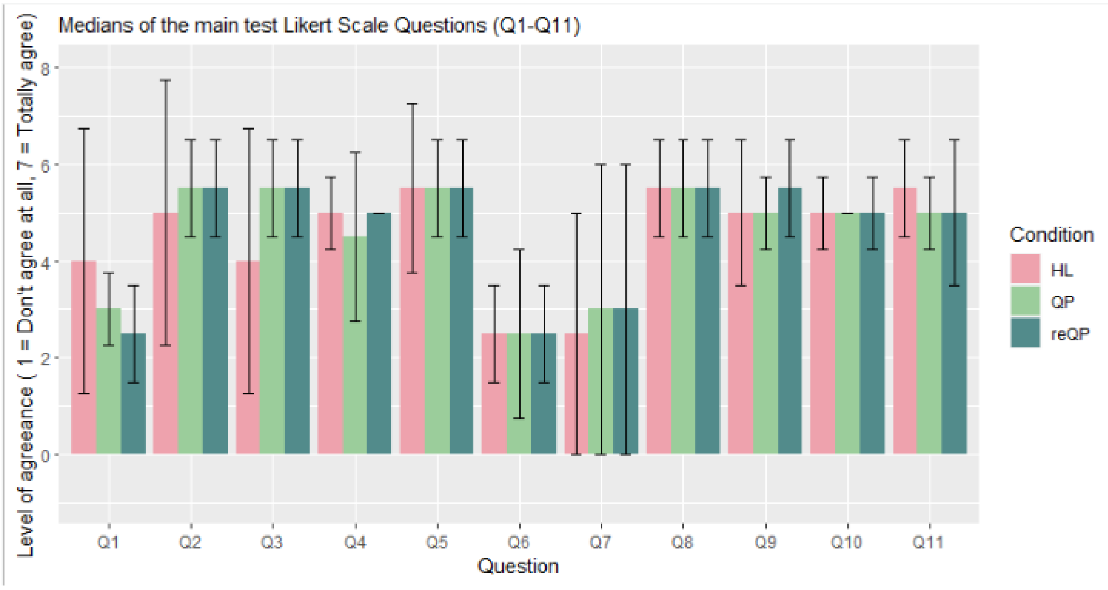

Figure 14 Medians and IQRs per question per condition of questions 1-11 of the ABI experience test.

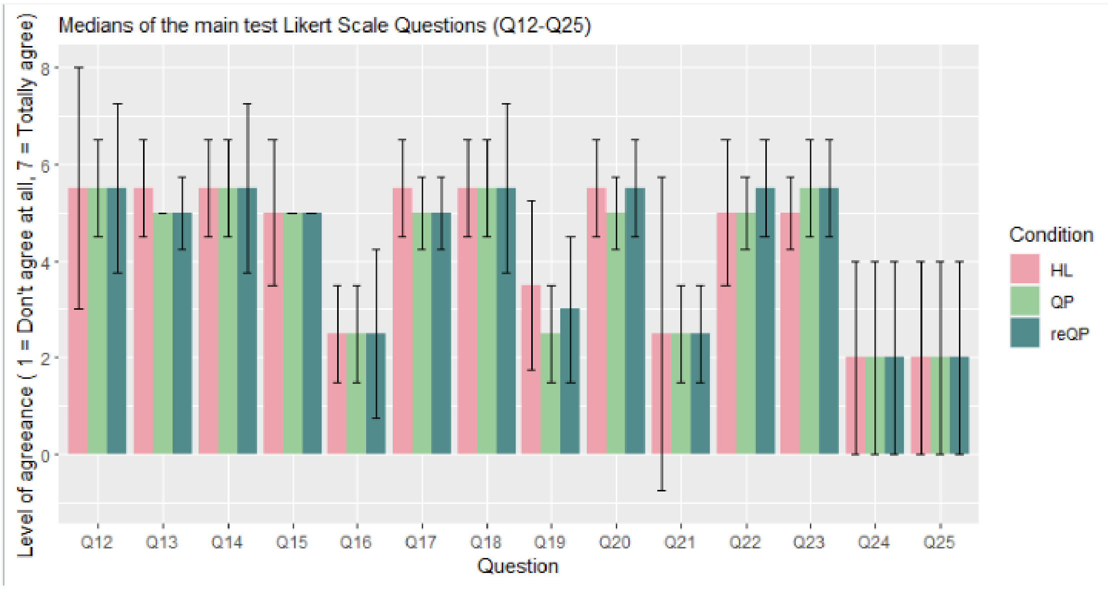

Figure 15 Medians and IQRs per question per condition of questions 12-25 of the ABI experience test.

Question	Median HL	Median QP	Median reQP
Q1	4.00 (2.75)	3.00 (0.75)	2.50 (1.00)
Q2	5.00 (2.75)	5.50 (1.00)	5.50 (1.00)
Q3	4.00 (2.75)	5.50 (1.00)	5.50 (1.00)
Q4	5.00 (0.75)	4.50 (1.75)	5.00 (0.00)
Q5	5.50 (1.75)	5.50 (1.00)	5.50 (1.00)
Q6	2.50 (1.00)	2.50 (1.75)	2.50 (1.00)
Q7	2.50 (2.50)	3.00 (3.00)	3.00 (3.00)
Q8	5.50 (1.00)	5.50 (1.00)	5.50 (1.00)
Q9	5.00 (1.50)	5.00 (0.75)	5.50 (1.00)
Q10	5.00 (0.75)	5.00 (0.00)	5.00 (0.75)
Q11	5.50 (1.00)	5.00 (0.75)	5.00 (1.50)
Q12	5.50 (2.50)	5.50 (1.00)	5.50 (1.75)
Q13	5.50 (1.00)	5.00 (0.00)	5.00 (0.75)
Q14	5.50 (1.00)	5.50 (1.00)	5.50 (1.75)
Q15	5.00 (1.50)	5.00 (0.00)	5.00 (0.00)
Q16	2.50 (1.00)	2.50 (1.00)	2.50 (1.75)
Q17	5.50 (1.00)	5.00 (0.75)	5.00 (0.75)
Q18	5.50 (1.00)	5.50 (1.00)	5.50 (1.75)
Q19	3.50 (1.75)	2.50 (1.00)	3.00 (1.75)
Q20	5.50 (1.00)	5.00 (.075)	5.50 (1.00)
Q21	2.50 (3.25)	2.50 (1.00)	2.50 (1.00)
Q22	5.00 (1.50)	5.00 (0.75)	5.50 (1.00)
Q23	5.00 (0.75)	5.50 (1.00)	5.50 (1.00)
Q24	2.00 (2.00)	2.00 (2.00)	2.00 (2.00)
Q25	2.00 (2.00	2.00 (2.00)	2.00 (2.00)

Table 12 The medians and IQRs per question of the Likert scale questions of the ABI experience test.

When analyzing the results, the first thing to be noted is that the majority of the results barely show a difference between conditions. All medians are between the scores of a 2.5 and 5.5 (where 1 = do not agree at all, and 7 = fully agree) except for the questions on motion sickness (Q24 and Q25) which both have a median score of 2. The questions that people disagreed with, so scoring below a 4, are questions that were negatively phrased such as '*my freedom of movement felt hindered when wearing the headset*' (Q6). This shows that overall, participants had quite positive experiences with the MR headsets and the three conditions.

Where some differences between conditions can be seen is in Q1 (*I had to search a lot to find the balls*), Q2 (*I had a good overview of the game)*, and Q3 (*I could easily find the balls)*. Q1 shows that participants had a slightly harder time with finding the balls when using the HoloLens 2 while the QP and reQP conditions are comparable (HL: 4.00 (2.75), QP: 3.00 (0.75), reQP: 2.50

(1.00)). In addition, the spread of the answers is a lot larger for the HL condition indicating that the experience varied more between patients in this condition. For Q2, the medians and the IQRs of the QP and reQP conditions are the same while that of the HL deviates (HL: 5.00 (2.75), QP: 5.50 (1.00), reQP: 5.50 (1.00)). Especially the IQR of the HL is again a lot higher than that of QP and reQP. This trend is also seen in the final question, Q3, where QP and reQP again have the same medians and IQRs while that of the HL deviates (HL: 4.00 (2.75), QP: 5.50 (1.00), reQP: 5.50 (1.00)).

7.2.3 Open Questions ABI Patients

For the open questions, 7 participants were included in the analysis (p1, p2, p3, p5, p6, p7, p9). P7 was excluded from the Likert scale questions because there needs to be a minimum amount of experience with a condition to be able to answer the questions which was lacking for them. However, the open answers are on all conditions, generally broader, and provide more context. Because p7 did wear the headset shortly and was able to get an impression of the headset, they were able to provide well-reasoned answers to the open answers meeting the minimum requirements to be included in the analysis.

The open questions consisted of 5 questions on the following topics: preference for condition, virtual/real world image, realism of virtual content, sense of control, and comfort of the headset.

Preference condition

The preferences were divided in terms of which specific condition they preferred, though the majority of the patients preferred the Quest Pro as headset over the HoloLens 2. 3 Participants preferred the conditions in which the Quest Pro was used over the HoloLens 2, though did not prefer either the QP or reQP condition specifically, 1 participant preferred reQP, 1 participant preferred QP, 1 participant preferred the HL, and 1 participant had no preference. Participants who preferred the Quest Pro over the HoloLens 2 argued that the image was clearer, it was easier to see the game, it was full screen without anything being cut off, and was more comfortable to look through. The participant who preferred the HL argued the game felt more realistic compared to QP or reQP.

Image quality

Four Participants did not see a difference in image quality for virtual content nor the real world and argued they could see the virtual content and real world equally well in all conditions. 2 participants could see the virtual content best in the QP and reQP and could see the real world best in QP, one of them also argued the darkening of the surrounding in reQP was unnecessary. 1 participant could see both the virtual content and the real world best in the HL as the virtual content felt more realistic and the real world was the same as looking through regular glasses. Even though some participants had a different experience in which they could see the virtual content and/or real world better, 5 of 7 participants didn't find it more important to either see the virtual content or real world better than the other. 1 Participant argued the combination of virtual content and the real world, and the balance between the two, was most important and 1 participant argued that the virtual content was most important as they were seated but explained the real world would become more important when they would have to move around in the space.

Realism virtual content

Five participants experienced the virtual content equally realistic in all conditions arguing it felt as if the balls were somewhat realistically hanging around them in all conditions. 1 participant argued that QP and reQP felt equally more realistic than the HL because no objects were cut off, and 1 participant argued the HL felt more realistic, however, not really being able to explain why rather than saying it was a feeling.

Control

Four participants felt equally in control in all conditions arguing they felt in control in all conditions. 1 Participant felt most in control during the QP condition because it was the most intuitive, 1 participant felt most in control during the reQP because it went the smoothest though it was also the third condition they tested, and 1 participant found most in control in QP and reQP equally because they had to search less.

Comfort

Four participants found the Quest Pro and HoloLens 2 equally comfortable to wear. They argued that both were lightweight and comfortable to wear, in addition a participant argued that the most important thing was that it wouldn't fall of while wearing the headset which both felt like they wouldn't do. 3 Participants found the Quest Pro more comfortable of whom 2 could not describe why, it was just a feeling, and the other participant argued it felt more robust than the HoloLens 2 which was a positive thing for them.

Lastly some general comments on the experience of using MR, some participants noted that they enjoyed using mixed reality for the first time, found it fun, and would use it during therapy if it had added value to their rehabilitation.

7.2.4 Behavioral Coding Scheme

For the behavior analysis, 5 Participants were included (p1, p2, p3, p5, p9). The behavior types were annotated resulting in a frequency per behavior type per condition which could be compared to each other. The medians and IQR for each behavior type were calculated and visualized, see Figure 16 and Table 13.

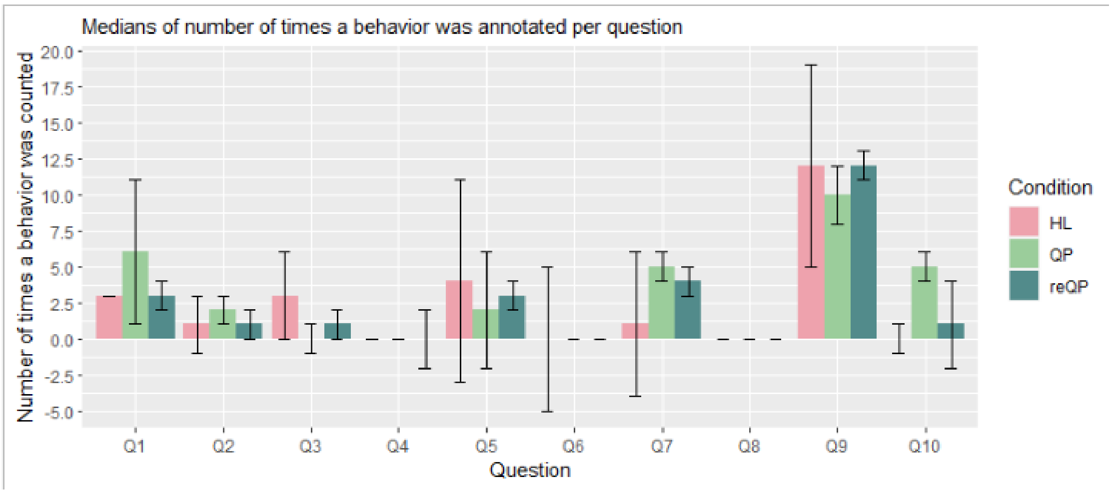

Figure 16 Medians and IQRs of the behavioral coding annotation of the recordings of the ABI experience test.

The majority of the behavior types, or questions, have comparable medians and IQRs between conditions. Some questions worth mentioning are Q1 (Check in), Q6 (Direction change vertical), and Q7 (Direct find). Q1 is interesting as the median of QP (6 (5)) is double the value of that of HL (3 (0)) and reQP (3 (1)). In addition, the IQR is also very large showing a large spread in responses. Q6 is notable as for all three conditions the median is 0 combined with an IQR of 0 for QP and reQP, whereas the IQR for HL is 5 which is rather high. So even though the medians of 0 suggest that the behavior has for most cases not been observed in all three conditions, the IQR of the HL condition shows a larger spread suggesting more frequent observations of vertical direction change in the HL condition. Last, Q7 shows a considerably lower median combined with a larger IQR for HL (1 (5)) compared to that of QP (5 (1)) and reQP (4 (1)). It shows that participants had less direct finds when using the HoloLens 2 compared to the Quest Pro.

	Behavior Code	HL median (IQR)	QP median (IQR)	reQP median (IQR)
Q1	Check in	3 (0)	6 (5)	3 (1)
Q2	Calm scanning	1 (2)	2 (1)	1 (1)
Q3	Rushed scanning	3 (3)	0 (1)	1 (1)
Q4	Change in scanning speed	0 (0)	0 (0)	0 (2)
Q5	Direction change horizontal	4 (7)	2 (4)	3 (3)
Q6	Direction change vertical	0 (5)	0 (0)	0 (0)
Q7	Direct find	1 (5)	5 (1)	4 (1)
Q8	Distraction external stimuli	0 (0)	0 (0)	0 (0)
Q9	Calm ball interaction	12 (7)	10 (2)	12 (1)
Q10	Impatient ball interaction	0 (1)	5 (1)	1 (3)

Table 13 The medians and IQRs per question for the behavioral coding annotation of the ABI experience test.

Inter-rater reliability test

For the inter-rater reliability test, 3 videos of the participants that were included in the behavior analysis were randomly selected, 1 of each condition, and annotated by an external researcher. The annotations of the external researcher and those of the main researcher were compared, see Table 14. In total there was an agreeance score of 53.3 % where both annotators fully agreed on the frequency. The behavior types where the annotators did not fully agree differed between a range of 1 and 4.

	Behavior code	HL P3 researcher	HL P3 external	QP P5 researcher	QP P5 external	reQP P9 researcher	reQP P9 external
Q1	Check in	**3**	**3**	**2**	**2**	2	0
Q2	Calm scanning	3	8	0	2	**1**	**1**
Q3	Rushed scanning	3	0	**0**	**0**	**2**	**2**
Q4	Change in scanning speed	**1**	**1**	**0**	**0**	**0**	**0**
Q5	Direction change horizontal	5	9	0	2	**3**	**3**
Q6	Direction change vertical	6	7	**0**	**0**	**0**	**0**
Q7	Direct find	1	3	10	7	**5**	**5**
Q8	Distraction external stimuli	**0**	**0**	**0**	**0**	**0**	**0**
Q9	Calm ball interaction	**12**	**12**	13	17	12	14
Q10	Impatient ball interaction	1	2	4	0	1	0

Table 14 Comparison between the annotations of the researcher and an external researcher of the recording of p3 (HL), p5 (QP), and p9 (reQP).

7.2.5 Time analysis

For the time analysis only participants 3, 5 and 9 were included as they were the only participants who completed all three conditions. The original idea was to compare the times of each individual ball and analyze the differences based on the locations of the balls, however, due to the small number of participants that fully completed the tests, this is not possible. Therefore, only the total completion times per condition of these participants are compared, together with the average per condition, see Table 15.

Participant	HL (in sec)	QP (in sec)	reQP (in sec)
P3	203.97	138.28	168.48
P5	278.37	224.96	226.07
P9	179.64	178.93	119.51
Average	**220.66**	**180.72**	**171.35**

Table 15 Average completion times of the participants who finished all three tests of the ABI experience test.

Here it can be seen that there is a large difference in the average completion times between the HL condition (220.66 sec) and both the Quest Pro conditions (QP: 180.72 sec, reQP: 171.35 sec), while the difference between the two Quest Pro conditions is a lot smaller making these two conditions comparable.

7.2.6 Feedback healthcare providers

The healthcare providers preferred the HoloLens 2 when it was used by the patients because they were able to have better eye contact with the patient. Even so, it was argued that when the patient was playing the game the contact with the patient was similar for both headsets as the patient was too busy to make direct eye contact with the healthcare provider. Similarly, while direct eye contact made it easier to judge what the patient was experiencing, it was for both headsets possible to judge how the patient was feeling as they were still able to see the patient's complexion.

Both healthcare providers argued an important addition to the headset would be a second screen on which they could see what the patient was seeing. The physical therapist argued it was important to be able to see what the patient is doing and what the goal is to be able to see the effect of the movements of the patient. An interesting note made by the rehabilitation doctor was the question whether they would still look at the face of the patient when they would have a second screen or would mostly be focused on the second screen and the task at hand.

The answers to the Likert scale questions of the physical therapist can be seen in Table 16. The largest differences can be seen in Q3, Q11, Q12. Q11 and Q12 which also tie together with what was previously discussed that a second screen could help with understanding what the patient is doing which could also help to know whether they need to intervene or not.

Question	Topic	HoloLens 2	Quest Pro
Q1	Patient and I had good communication	4	2
Q2	I looked at the patient during the task	5	5
Q3	Felt seen by patient	4	1
Q4	Felt shut out by headset	3	4
Q5	Headset disturbed the communication	4	5
Q6	Important to be able to look at the patient	5	5
Q7	Could judge how patient was feeling	5	6
Q8	Could judge how patient was feeling through facial expressions	6	6
Q9	Patient understood the instructions	5	4
Q10	Felt heard by patient	5	3
Q11	Could judge if it was needed to step in	4	1
Q12	Understood what the patient was doing	4	1
Q13	Paid attention to arm movements of patient	5	6
Q14	Patient made correct arm movements	5	6
Q15	Would use it during therapy	4	5

Table 16 Results of the Likert scale questions of the HoloLens 2 and Quest Pro (played with MPT) where 1 = strongly disagree, 4 = neutral, and 7 = totally agree.

7.3 Discussion

As the ABI experience test consisted of numerous measuring tools, this discussion section aims to bring together the different results and tie them together to provide a cohesive overview of the most important findings. These findings will be discussed further in the next chapter where they will be compared to the findings of the Design exploration tests and be put in scientific context. Furthermore, this discussion section will discuss the limitations of the ABI experience test.

7.3.1 Results

The most notable differences found in the Likert scale questions are part of the theme spatial awareness of the patients where there were notable differences between the HL condition and Quest Pro conditions while QP and reQP were comparable. These results showed that participants had a harder time finding the balls with the HoloLens 2 compared to the Quest Pro. These results were also found in the behavioral coding scheme where participants showed more search behavior with the HoloLens 2 and less direct finds. From these results it can be argued that in the Quest Pro patients had a better overview of the game which made it easier to find balls in the game which in turn lead to more direct finds as observed in the recordings. This can also be tied together with the open answers where participants found it easier to see the game through the Quest Pro and preferred it as no content was cut off.

While these differences were found between the HoloLens 2 condition and both Quest Pro conditions, no differences were found between the two Quest Pro conditions. This can be seen in both the Likert scale questions and the majority of the behavior analysis. Similarly, in the open questions, when asking which condition the participants preferred, they often answered with both QP and reQP arguing that between those two conditions they did not have a preference. To take it a step further, when asked if they noticed a difference between the two conditions and what that might be, several participants said they did not notice a difference or could not name a difference. All these results would imply that even though an effort was made to create a different type of experience in the game design of reQP, participants did not experience as such.

There was one type of behavior that did show a slight indication of difference between the QP and the other conditions, including the reQP condition. In the behavior analysis, the QP condition showed the highest median and IQR for the check in frequency, double that of reQP and HL. As it is the only behavior type that showed any noteworthy difference between QP and reQP, it might indicate that there is a difference in check in behavior between conditions including QP and reQP even though participants didn't experience it as such. This potential difference between the QP and reQP could also be interesting for the topic of focus. One of the expected benefits of the redesign was to potentially heighten the focus by blurring external distractions. The slight difference in check in frequency might also have implications for the level of focus as for a check in to occur, the participants need to take their focus from the game and change it to the researcher/therapist. As the reQP condition showed a lower median for check ins than the QP condition, this might also indicate that the reQP could be beneficial to increase focus. However, as there is only a small difference and there were no other external stimuli, the influence of reQP on the focus should be further explored before any conclusions can be drawn.

Furthermore, it is interesting that the HL also shows such a low number of check ins as it does not occlude the real world and the researcher/therapist like in the reQP condition. Two explanations could be thought of; first it could be that due to the smaller FoV and lower spatial awareness, participants are more focused on finding the balls as it is more challenging. This would tie together with the previous argument where an increased sense of focus would decrease the check in frequency. However, another explanation could be that some of the tests of the HL were cut short due to technical problems resulting in a lower number of observations and similarly, potentially lower check in frequencies. If this would be the case, it would also have implications for the other behavior type observations, resulting in the HL condition having consistently lower observations than the Quest Pro conditions. As this is not the case, this explanation is disregarded.

Lastly on a different note, while most patients preferred the Quest Pro for various reasons, the therapists preferred the HoloLens 2 mainly due to the possibility of having eye contact with the patient. Even so, they did argue that the communication and the ability to read the emotional state of the patients were comparable in both headsets. In addition, one of the therapists observed that in order to have eye contact, they had to find the right angle as the eyes of the patient got blocked by the virtual content of the glasses when they looked from straight ahead. The most important additional feedback the therapists provided was that a second screen on which they could watch along with the patients was needed to be able to guide the patient better. This raises the question of when a second screen would be added, how often would the therapist look directly at the patient and of how much importance the direct eye contact would still hold. It is expected that when a second screen would be added, the focus would be more divided between the patient and the second screen.

7.3.2 Limitations

While the expectation was that MPT would be most suitable for the HoloLens 2, it turned out that the HoloLens 2 actually experienced the most problems of the two headsets during testing.

First of all, the game used the gaze function of MRTK, a mixed-reality toolkit for Unity, and while the Quest Pro only took the headset position as input for the gaze, the HoloLens 2 used eye tracking as input. Eye tracking can be more accurate compared to the headset position; however, it is highly sensitive to different people leading to not providing any input when the user is changed (for example from the researcher to the patient). To avoid this problem, an eye calibration was needed for each person when putting on the headset. However, this problem was discovered after already testing with the first two participants which led to them being unable to finish the HL condition as the headset was not responding to their gaze. This function was not used during the Design exploration tests and was added to take into account the limited upper limb function of ABI patients, however, because it was not previously tested this problem was not discovered yet. The sensitivity of the eye tracking could be problematic when used in therapy as numerous different people would need to be able to wear the headset. Having to do an eye calibration every time would make it harder to use and less user friendly.

Second, the playing field had to be set up manually, so the playing field was made to be slightly visible to be able to align the playing field with the table. While the visible playing field was no problem in the Quest Pro, it was distracting in the HoloLens 2 as it highlighted the smaller FoV because the playing field was cut off at the edges of the FoV. In addition, the color of the playing field was distorted in the HoloLens 2, the playing field was supposed to be white and mostly see through, however, it was rather opaque with spotty pinkish colors mixed in. This is most likely caused by the way light influences virtual content and their colors in optical see-through headsets. While none of the participants mentioned noticing these effects, it still could have influenced the experience.

Last, the game froze during several tests while using the HoloLens 2. The reason for this has not been found as the game did not freeze during the numerous tests that were done by me and my colleague prior to starting the ABI experience test. Also, the game never froze while using the Quest Pro which suggests that the problem is linked specifically to the HoloLens 2 rather than the game in general. An explanation could be that the HoloLens 2 experienced difficulties with computing power when running the game, making recordings, and switching between the game, the eye calibration and back to the game, all at the same time. Another possibility could be that there is a bug somewhere in the code specifically for the HoloLens 2, however, me and my colleague have not been able to find this.

Lastly, a general problem with the game was that the patient experienced the interaction with the balls as too sensitive. The balls are activated from the first moment of touch and sets the direction to move towards based on that moment of touch and where the ball is touched. This led to balls moving into counter intuitive directions, especially when patients would make wild movements. I tried to provide instructions on how to hit the ball so it would be more successful, however, many patients would not adopt these instructions leading to patients feeling frustrated by the game. The game should be more suitable for a wide range of players and move as expected rather than needing instructions on how to play the ball specifically.

7.4 Summary Main Findings

The aim of the ABI experience test was to investigate how the differentiating features of optical see-through (HoloLens 2) and video see-through (Quest Pro) differently affected the experience of upper limb motor rehabilitation of ABI patients from the perspective of the patient and the therapist.

While there were some notable differences found on the topic op spatial awareness of the patient, there were little differences in experience found on other topics between conditions. This was especially the case for the QP and reQP conditions where patients did not notice a difference in game design and experience. Even though they could not differentiate between these two conditions, patients did show a preference for the Quest Pro in general. They argued they had more of an overview of the game and could see the game better due to a clearer image, both virtual content and the real world. In terms of comfort, patients did not have a preference for one of the headsets and found both comfortable. Similarly, there was no indication that either of the headset caused a form of simulation sickness.

While patients had preferences for the Quest Pro, therapists preferred the HoloLens 2 as it allowed for eye contact with the patient which gave an indication on what the patient was experiencing. Even so, they could judge the emotional state of the patient and still communicate well with the patient while using the Quest Pro. The most important addition to both headsets would be a second screen to watch along with the patient.

8. Overall Discussion

In the overall discussion the aim is to combine the findings from the different stages and tests from this thesis and discuss their potential implications in regard to previous work. First the differentiating features of the MR systems as presented in the Design exploration tests will be discussed per feature. This is followed by a discussion on the target group, ABI patients, and how they specifically experienced and handled MR. Next, implications for future game design in general and specifically for rehabilitation will be discussed. Last, suggestions for future works will be offered.

8.1 Characteristic Differences of MR Headsets

8.1.1 Spatial awareness

In this study, spatial awareness was used as an umbrella term consisting of topics such as finding game objects, being aware of the location of virtual objects and being aware of the space in the real world. Spatial awareness, and more specifically finding game objects, was the main topic in which significant differences were found, and the only topic in which meaningful differences were found in both the Design exploration tests and the ABI experience test. Participants experienced a harder time finding game objects when using the HoloLens 2 in the ABI experience test which can most likely be explained by the FoV size as participants showed the same results in the FoV test. Because the FoV test used the same headset, the Quest Pro, in both conditions and only altered the FoV size, it can be linked to this feature. So, with a smaller FoV, participants had to search more, and weren't as sure if they found all objects. These results were also supported by the open answers where participants argued that they had less of an overview of the game which also made it feel less calm. These results support previous findings where they found that the FoV size had significant effects on search tasks (Creem-Regehr et al., 2005).

Furthermore, spatial awareness also includes being aware where and of how far the virtual objects are located from the user. The results showed there was no indication that participants had a harder time estimating how far virtual objects were from them, or more generally, judge where the objects were in the environment. This is in line with previous work where they argued that the FoV size does not necessarily cause depth estimation failures for virtual content (Knapp & Loomis, 2003; Kruijff et al., 2010). In addition to these previous findings, my results show that the type of MR and how to virtual objects are presented to the user also has no influence on the depth estimation of the virtual object to the user.

Besides the spatial awareness of the virtual content of the headset, no significant differences were found on being aware of their surroundings and having less spatial awareness in the real world. These results are in accordance with previous studies who found that HMDs and the FoV size have no influence on distance perception in the real-world (Creem-Regehr et al., 2005; Knapp & Loomis, 2003). While the study by Creem-Regehr et al. looked at HMDs and FoV size, other studies found that the type of display can have an influence on the depth perception. They found that people will underestimate egocentric distances, the distance between observer and an external point in space, up to 50% while wearing video-based HMDs (Knapp & Loomis, 2003; Piryankova et al., 2013). Their findings are contrary to my findings where participants did not show differences, or problems in general, with depth perception in the different MR HMDs. Participants argued in the Design exploration tests and the ABI experience test that they were aware of their surroundings and could move around freely in both headsets. Also, no difference in behavior towards physical objects were observed. A possible explanation for this difference could be due to the previous studies being of 10 years ago, in that time XR systems and the types of displays have been further developed and improved, such as the application of binocular overlap to create a better depth perception (Boger, 2016; Butz et al., 2022). However, as depth perception was not a main topic or focus of this study, further research to confirm these findings and possible explanation is needed.

8.1.2 FoV size

As previously discussed, the FoV size mostly had an influence on the spatial awareness, in particular the search behavior of participants. Interestingly, while participants did not experience a difference in their freedom of movement or behavior, there was a difference in search behavior that could be observed with different FoV sizes. What makes it more interesting is that the way the search behavior got affected by the FoV size differed between the Design exploration tests and the ABI experience test which can most likely be linked to the difference in doing the tests seated or while walking.

In the FoV test the participants walked around through a space to find all objects. A smaller FoV would make participants slow down and walk around more carefully compared to the larger FoV. The opposite was found in the ABI experience test where participants were seated and would show more rushed search behavior with slightly more vertical and horizontal switches with a smaller FoV. A possible explanation could be that when participants are walking around while playing a MR game, there is a need to pay attention to their surroundings and avoid collision with objects. While the smaller FoV decreases the size in which the virtual objects are shown, the view of the real world stays the same. However, as the FoV size decreases, participants need to search harder to find objects which increases their level of required focus on the game but at the same time they need to keep an eye out for their surroundings. So due to this divide in attention, when the smaller FoV size requires more attention on the game, their attention for their surrounding decreases so they will move slower to avoid collisions. This is supported by previous studies who report that cognitive tasks decrease the walking speed of healthy adults while performing a dual task (Wrightson et al., 2016). This is done to decrease the cognitive cost of dual task walking and more energy can go into the cognitive task at hand (Patel et al., 2014). On the contrary, when the task is done seated, this need to avoid objects is gone so the full attention can go to the game. So, when the FoV size decreases, participants need to search harder which can be increased by moving or searching faster. While seated, the task is a single task rather than a dual task which generally allows for faster movements, both in healthy participants and in ABI patients (H. Kim et al., 2021). These findings can have implications in regard to how MR should be employed during rehabilitation as evoking the right and meaningful movements is required for succesful recovery.

On a different note, the FoV size also seemed to have some influence on the realism of the virtual content. It was argued in the Design exploration tests that a larger FoV increased the realism of the virtual objects and made it feel as if the objects were really there. This is in line with previous work which also argued that a smaller FoV decreases the realism due to the objects being cut off (Brunzini et al., 2022). Interestingly, these results did not show in the ABI experience test as the participants found the virtual content equally realistic in all conditions. A potential explanation could be that ABI patients are generally less outspoken in their opinions, which will be further discussed in section 8.2, and might not have experienced a distinct difference between the realism of the two headsets, or they might not have found it worth mentioning.

8.1.3 Quality of image

In regard to image quality, both headsets, and video see-through and optical see-through in general, have their own tradeoffs.

Video see-through generally shows better quality virtual content as it is opaque and is not influenced as much by external light sources. However, the image quality of the real world is dependent on the hardware of the headset. When looking at the Quest Pro, the quality of the real world is generally of poor quality which also was one of the main arguments of participants in the Cooperation test to prefer the HoloLens 2 over the Quest Pro. Other reviews on the Quest Pro experienced similar problems, Guttag (2023) tested the Quest Pro on the classic Snellen eye chart and was unable to read any of the letters (Guttag, 2023). Interestingly, the participants in the ABI experience test did not experience it as such and often rated the Quest Pro as having the clearest image, both virtual content and the real world. This could possibly be explained by that their focus was mostly on the game and, as there was no need to walk around or be specifically aware of their surroundings, did not look in detail at the image quality of the real world. Even so, it can be stated that the image quality is of low quality, however, as this is a hardware problem it can be expected that later models will have an improved image quality, also depending on the specific headset used.

Optical see-through was generally experienced as having an overall lighter image and, according to the Design exploration tests, being able to see the real world better. As argued by one of the participants in the ABI experience test, it is as looking through regular glasses when looking at the real world. The image quality of the virtual content is very dependent on the setting and the type and intensity of the light. With bright direct light the virtual content becomes very see through and less realistic which was also the experience in a study by Brunzini et al. (2022) where they tested with the HoloLens (Brunzini et al., 2022). Similarly, the colors of the virtual content can also be altered by different light sources which is especially apparent in larger surfaces.

8.1.4 Eye contact

Previous work argues that eye contact between patients and physicians is important to the relationship between the two as sub-optimal levels of gaze might reduce trust of patients in their physicians (Jongerius et al., 2022; MacDonald, 2009). In addition, it can be important to judge when to intervene during therapy as was argued by the therapists in the context exploration, in addition to the general complexion of patients and general movements. So, when applied to MR HMDs, there was a preference for the HoloLens 2 from the perspective of the partner/therapist in both the Cooperation test and the ABI experience test, as it allowed for eye contact with the headset wearer. However, even when they were not able to have direct eye contact, they were still able to read the emotional state of the headset wearer through the overall complexion and the tone of the voice of the headset wearer.

Furthermore, from the point of view of the headset wearer there was no difference found in the capability of heaving direct eye contact with others while wearing the HMD as this was possible in both headsets. There were some participants in the Cooperation test who argued that they could see the environment better in the HoloLens 2 resulting in also seeing their partner better. Still, overall the headsets or type of MR did not influence the collaboration between participants in the Cooperation test or between the ABI patients and the therapist/research in the ABI experience test.

As the previous studies argue that gaze is mainly important for the patient's sake, it can be stated that this is not a problem in the case of MR as the patient is still able to look at other people in the room. In addition, while therapists do prefer to have eye contact with the patients, they are still able to judge when to intervene as they can still see the complexion of the patient and their general movements. It should still be considered as a preferable option, though it does not have to be a requirement for MR being employed during therapy.

8.1.5 Simulation sickness

Simulation sickness was considered a concern prior to testing as literature suggested that video see-through was more likely to cause a form of simulation sickness than optical see-through (Ballestin et al., 2021). However, the results from both the Cooperation test and the ABI experience test show no indication that one of the headsets cause a form of simulation sickness. In addition, previous studies found that the posture, meaning sitting or standing, can also contribute to simulation sickness where standing was more prone to lead to simulation sickness (Zielasko & Riecke, 2021). However, my results argue that there is no evidence that the posture would influence the level of simulation sickness experienced. Though it should be noted that that it is recognized that multiple factors contribute and interact with simulation sickness so that it is difficult to pinpoint what the direct cause can be (E. Chang et al., 2020; Zielasko & Riecke, 2021). Even so, the fact that my results indicate that the type of MR headset show no cause of simulation sickness is positive for the employment of MR during rehabilitation.

8.1.6 General comfort

When looking at general comfort there are a few aspects to consider, such as the feel on the head and how it influences fatigue in users. In terms of the feeling on the head, there doesn't seem to be one favorite headset. According to previous reviews, the weight and weight distribution of the headsets differ where some reviews argued that the Quest Pro was less comfortable than the HoloLens 2 when using it for a longer period of time, as it was heavier and put more pressure on the forehead (Brown, n.d.-b; VRX, 2023a). And while some participants agreed and preferred the HoloLens 2 due to being more light weight, others preferred the Quest Pro exactly for the opposite reason that it felt more robust. Overall, people do not have a strong preference towards one of the headsets and found both quite comfortable to wear. It should be noted that the headsets were only worn for a short period of time instead of a prolonged period which could also play a role in the lack of preference. However, in the context of rehabilitation it is expected that patients would also wear the headset for a relatively short period of time during therapy.

Moreover, during the interviews therapists mentioned that ABI patients are prone to fatigue in general, so also during therapy. Previous studies also show that fatigue is a common complaint after a stroke where about 39 – 72% of stroke patients experience this (Colle et al., 2006). It was therefor included in the Likert scale questions of the ABI experience test, however, there were no indications of MR causing increased fatigue in patients. This could also be because the ABI patients were sitting during the test which also decreases the chances of fatigue while using XR (Zielasko & Riecke, 2021). However, even while sitting the results indicate that there is no difference between MR systems in causing fatigue.

8.2 ABI patients' view on MR

The main target group of this thesis was ABI patients and how they experienced different mixed reality types. By testing with healthy participants in the design exploration test and ABI patients in the ABI experience test, a comparison between groups is possible allowing to gain insight in how they experience of ABI patients might differ, as has also been done in the previous sections. In the design exploration test, healthy participants generally seemed to be more critical and outspoken about their experience with the different headsets compared to ABI patients. In the Likert scale questions ABI patients applied little variation in answers and mostly answered either in terms of agree or disagree. Similarly, in the open answers ABI patients would give very short answers and often did not prefer on of the options or did not notice a difference between conditions. This might be explained by the effects of an ABI on the mood and emotions of people. Previous studies showed that people who suffered a stroke show, among others, increased indifference and pragnosia meaning defective social communication style (Ferro & Santos, 2020; Nelson et al., 1993). While this doesn't apply to everyone and the level in which it shows depends per person, it is likely that this did play some role in the limited responses provided by the ABI patients. This makes it more difficult to go deeper in what is at the core of an optimal experience for ABI patients. On the flip side, it makes them less critical which can be beneficial in creating meaningful MR experiences.

Overall, ABI patients had a positive experience with the different MR headsets. While the majority of the participants preferred the Quest Pro as headset, they did not dislike the HoloLens 2 or had negative experiences. In general, they argued they would be open to using either MR headset as long as it would be useful to their rehabilitation. This motivation was also provided in the context exploration where they explained they were willing to try any type of technology as long as it was beneficial for their recovery. And while games can be useful in increasing motivation during rehabilitation (Swanson & Whittinghill, 2015), the main motivator is to get home independently as argued in context exploration and previous studies (Maclean, 2000). This might also be part of the reason that ABI patients were less outspoken about the differences between headsets, it is perceived as a tool rather than just a fun game, meaning that the outcome is prioritized over the way it is offered. In contrast, for healthy participants the MR experience was more likely seen as a fun game without a specific purpose. This results in the goals and reasons for using MR are very different between groups which likely influenced how participants experienced the headsets and reported their experiences. Even so, ABI patients were motivated to use the technology and would use it again, this is in line with previous research who looked at the user experience with a VR system using wearable data gloves and a monitor for upper limb rehabilitation (Pallesen et al., 2018).

8.3 Game Design

Adaptation to games are needed to fit the heterogeneous nature of ABI-related dysfunctions to prevent frustration when the game or control of input devices are not fitting (Barrett et al., 2016; Lohse et al., 2014). This was seen in the work by Pallesen et al. (2018), but also in ABI experience test where participants got frustrated by the game when it was not responding accordingly to their arm movements. More generally, it would be beneficial to work in an iterative manner when designing a rehabilitation game, and more generally any game, where tests in between are conducted. These tests can help identify potential problems for the target group, in this case ABI patients, and help apply required adaptions to make the game more effective and enjoyable. In terms of the game design used in the ABI experience test, it could have helped to identify problems regarding the eye calibration test in the HoloLens 2 and the previously mentioned ball sensitivity before actually doing the final testing. Due to restricted availability of test subjects this was not possible for my thesis, though, if possible it would be recommended for future research and game development.

When looking at specific features that are important in the game design for upper limb rehabilitation of ABI patients, the main motivator of patients should be considered, which is to improve motor skills. The enjoyment during playing is ofcourse important as it helps to motivate patients and to let them want to keep playing which is also beneficial to their recovery (Primack et al., 2012), however, the game should prioritize intentional movements. In the ABI experience test it was clear to see that patients were at varying stages in their rehabilitation meaning that they needed different types of movements to make them meaningful. To accommodate for this a game would benefit from having adaptable difficulty depending on the motor skill level of patients. From the ABI experience test, these features stood out the most to include in the core of game design for rehabilitation, regardless of the setting or type of motor rehabilitation. They are in accordance with the research by Barrett et al. (2016) who provide an overview of game design principles for stroke rehabilitation games.

While Barrett et al. (2016) gave a comprehensive general overview, it did not dive deeper into the possible effects of different therapy settings and how the game design could be utilized. In my redesign I tried to accommodate for the fact that therapy is often done in group settings with more external stimuli. However, games are most beneficial, and movements are more likely to be of higher quality, when the patient has their full attention on the game without being distracted by external stimuli. As this is more likely to occur during group therapies, the background was darkened to draw the attention towards the game and playing field, with the added benefit of drawing the attention away from the poor-quality surroundings as this negatively contributed to the experience during the Design exploration tests. While there were slight indications that participants were more focused on the game with the darkened surroundings, the results weren't enough to draw strong conclusions, especially as the test was eventually done in a calm office setting rather than the intended group setting. For future game design the therapy setting is a factor to consider as it is likely to influence the game experience. Though, further research should be done to better understand what the best approach is to design for group therapy settings.

Lastly, the results from both the design exploration test and ABI experience test showed the importance of choosing the right hardware for the game, and vice versa, designing the game to match the hardware. In the game design the aim was to build a game that was multiplatform and would work on both headsets, and while it did work on both headsets, they did not perform equally well. In the Design exploration tests the HoloLens 2 was working really steady and people enjoyed it while the Quest Pro showed some flaws, such as the light source causing flickering images. On the contrary, during the ABI experience test these flaws were fixed in the Quest Pro, but the HoloLens 2 showed flaws with distorted colors in large surfaces and the game that froze multiple times. While these flaws could have been fixed through an iterative design process as suggested previously, it does highlight the importance of understanding the possible effects of specific features of the headsets on the experience of users.

8.4 Future Works

While this research took the first step in researching the influence of mixed reality on the experience of ABI patients during rehabilitation, it experienced quite some limitations resulting in limited data to work with. While this research can serve as an exploration of where the differences might be and how they could affect the experience, further research is needed to draw solid conclusions.

Research on the how the experiences of ABI patients and their therapists are influenced by MR or other forms of XR during motor rehabilitation should be continued. Again, the results from this thesis show slight indications of certain features influencing the experience which, when better understood, really have the potential to improve the rehabilitation experience using MR. However, this should be done in a more systematic manner with an iterative design process and more included subjects to get better results which can be more generalized. These conclusions will be useful in future research when deciding what headset to use and can help explain findings, in addition it can be useful to healthcare institutions on deciding how to apply MR.

Last, as addition to the experience, research on how the quality of movement is affected by different MR systems should be done to explore its effect on rehabilitation. Some results of this thesis indicate that there might be a disconnect between how people experience a headset and how they think they move, and their actual observed movements. To be able to employ mixed reality and decide on what type of technology should be used in rehabilitation and other health care sectors, it is important to understand how these systems differently affect the movements so the best system can be used.

9. Conclusion

The aim of this thesis was to create a better understanding of how differentiating features of optical see-through and video see-through mixed reality affect the experience of upper limb motor rehabilitation of ABI patients from the perspective of the patient and the therapist, and by doing so, potentially improve the quality of rehabilitation.

One of the main motivators for this study was that previous researches provided no motivation or specifications for their chosen XR hardware. However, my findings show that the hardware has an influence on the experience of users, showing the importance of reporting this in studies as it can benefit future research. A number of differentiating features showed an influence on the ABI patients' experience with MR, and for MR users in general. There are implications that the type of MR, due to the FoV size, has an influence on the way people behave, search, and move around without the users noticing it. Interestingly, the way the behavior got altered by the FoV size differed between the Design exploration tests and the ABI experience test. It is expected that this difference is caused by the difference in posture where a smaller FoV would lead to participants moving slower while walking and moving faster while sitting. This can have implications for the use of MR during rehabilitation when certain movements are important for recovery. This is especially important as my thesis showed that patients are open towards the use of MR, as long as it is beneficial to their recovery. Though, the type of MR did not seem to matter for them which is likely due to an increased indifference that is more often seen in ABI patients. While this can make it more difficult to gather meaningful findings in research, it can also make it easier to create game designs and match hardware that are meaningful in rehabilitation.

Finally, this thesis showed the potential that MR has and how different features can be utilized to create a more positive experience for ABI rehabilitation. As final note to HoloMoves and others who want to apply XR to rehabilitation, as mentioned, this thesis showed that ABI patients are open towards the use of novel technologies, though they did highlight they enjoyed seeing the real world while seeing virtual content. Because of this, forms of AR and MR are recommended over forms of VR in terms of motor rehabilitation. Furthermore, due to the implications that the type of MR headset and the posture of the user influences their movements, it is recommended this is taken into consideration during the testing phase so that the required movements for rehabilitation are controlled for, and to be able to match the right headset to the rehabilitation goal.

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12. Appendix

As the participants were all Dutch, all questionnaires used in this thesis and presented in this appendix are in Dutch.

12.1 Interview Questions Used in the Context Exploration

CVA-patiënten:

Persoonlijk

1. Wat is uw leeftijd?
2. Hoe identificeert u zich? (man/vrouw/anders)
3. Wat zijn uw beperkingen ten gevolge van de CVA?
4. Hoe lang geleden is de CVA? / Hoelang ontvangt u nu revalidatie?

Revalidatie algemeen

5. Hoe ervaart u revalidatie in het algemeen?
6. Welke onderdelen van revalidatie zijn belangrijk voor u?
7. Wat zijn onderdelen van de revalidatie die u nu als fijn ervaart?
8. Waar krijgt u motivatie van?
9. Wat zijn onderdelen van revalidatie die u nu mist?
10. Als u 1 ding mocht veranderen, wat zou dat dan zijn?

Fysiotherapie

11. Wat vindt u in het algemeen van de therapie die u ontvangt?
12. Hoe vaak per dag/week ontvangt u therapie?
13. Hoe ziet een therapiesessie er voor u uit?
14. Wat voor oefeningen doet u tijdens een therapiesessie?
15. Wat voor oefeningen moet u individueel doen?
16. Waar bent u nu blij mee bij uw behandelingen?
17. Wat is op het moment uw grootste frustratie?

Interactie zorgverlener

18. Hoe ziet interactie met een zorgverlener eruit? (Instructies/samen oefeningen doen/vragen stellen?)
19. Is de interactie met de zorgverlener tijdens de revalidatie belangrijk voor u?
    a. Zo ja, welke aspecten/waarom? Zo niet, waarom niet?

Technologie

20. Hoe handig bent u met technologie? / Hoe zijn uw digitale vaardigheden?
21. Hoeveel affiniteit heeft u met technologie?
22. Heeft u wel eens AR/MR/VR gedaan?
23. Zou u tijdens revalidatie gebruik maken van innovatieve technologie?
    a. Zo ja, waarom wel?
    b. Wat zouden dealbreakers zijn waardoor u geen technologie zou gebruiken?
    c. Zo niet, waarom niet?
    d. Is er iets wat u zou kunnen overtuigen om het wel te gebruiken? (positieve gevolgen/leuker/meer motiverend?)

Zorgverleners:

Persoonlijk

1. Wat is uw leeftijd?
2. Hoe identificeert u zich? (man/vrouw/anders)
3. Wat is uw rol binnen de revalidatie van CVA-patiënten
4. Hoe lang werkt u al in deze positie?

Revalidatie algemeen

5. Welke onderdelen van revalidatie zijn belangrijk voor u en waarom?
6. Wat motiveert u tijdens uw werk?
7. Wat zijn onderdelen van revalidatie die u nu mist?
8. Als u 1 ding mocht veranderen, wat zou dat dan zijn?

Rol specifiek

9. Hoe ziet een behandeling met een patiënt er voor u uit?
10. Wat voor handelingen zijn onderdeel van een behandeling?
11. Wat zijn uw doelen tijdens een behandeling?
12. Op wat voor momenten grijpt u wel eens in tijdens een behandeling?
13. Hoe beoordeelt u of u moet ingrijpen?
14. Hoe ziet een ingrijp er dan uit?

Interactie met patiënt

15. Hoeveel patiënten ziet u op een dag?
16. Hoeveel contact (moment/uren) heeft u met een individuele patiënt?
17. Hoe is uw band met een patiënt? (formeel/informeel)
18. Wat is belangrijk voor u tijdens contact met patiënten?
19. Is de connectie met de patiënt tijdens de therapie belangrijk voor u?
    a. Zo ja, welke aspecten/waarom?

Technologie

20. Hoe handig bent u met technologie? / Hoe zijn uw digitale vaardigheden?
21. Hoeveel affiniteit heeft u met technologie?
22. Heeft u wel eens AR/MR/VR gedaan?
23. Zou u tijdens revalidatie gebruik maken van innovatieve technologie?
    a. Zo ja, waarom wel?
    b. Wat zouden dealbreakers zijn waardoor u geen technologie zou gebruiken?
    c. Zo niet, waarom niet?
    d. Is er iets wat u zou kunnen overtuigen om het wel te gebruiken? (positieve gevolgen/leuker/meer motiverend?)

12.2 Design Exploration tests

12.2.1 Questionnaire FoV test

Wordt ingevuld door onderzoeker

Participant nummer:

Naam:

Leeftijd:

Geslacht:

Volgorde test:

- HoloLens2 – Quest
- Quest – HoloLens2

Likert schaal

Na elke condities zal u gevraagd worden om 15 vragen in te vullen aan de hand van een Likert Schaal zoals hieronder is weergegeven. Hierbij wordt een statement gegeven waarna u een hokje kan aankruisen dat aangeeft hoe erg u het eens bent met de stelling. Hierbij is 1 er totaal mee oneens zijn, 4 is neutraal/geen mening, en 7 volledig mee eens.

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

Open vragen

Nadat u beide condities heeft getest zullen u nog 6 open vragen gesteld worden naar uw ervaring met de twee condities.

Likert Schaal Vragen Field of View test

Kruis 1 hokje aan die het best overeenkomt met je ervaring.

Ruimtelijk bewustzijn

1. Ik had het idee dat ik wist of ik alle ballen had gevonden

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

2. Ik moest veel zoeken voordat ik alle ballen had gevonden

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

3. Ik had het gevoel dat ik wist waar andere ballen zich bevonden in de ruimte

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

4. Ik had het gevoel dat ik de volgende bal makkelijk kon vinden

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

5. Ik had het gevoel dat ik wist hoe ver de ballen van me vandaan waren

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

Bewegingsvrijheid

6. Ik voelde me zelfverzekerd tijdens de taak

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

7. Het voelde alsof ik me vrij kon bewegen door de ruimte

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

8. Ik had het gevoel dat ik in controle was

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

9. Ik voelde me belemmerd in mijn bewegingen

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

10. Ik had het gevoel dat ik voorzichtig moest zijn tijdens mijn bewegingen

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

Algemeen

11. Ik had het gevoel dat ik wist wat ik moest doen

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

12. Beperkt in het beeld virtuele content kunnen zien was belemmerend voor het spel

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

13. Ik vond de taak lastig

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

14. Het voelde alsof de ballen echt om me heen hingen

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

15. Ik had het gevoel dat ik kon interacteren met de ballen

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

Open Vragen FoV test

Beschrijf in uw eigen woorden hoe u de verschillende condities heeft ervaren naar aanleiding van de vragen.

1. Welke mixed reality ervaring had uw voorkeur?
    a. Leg alstublieft uit waarom

2. In welke bril had u het meest het gevoel in controle te zijn?
    a. Leg alstublieft uit waarom

3. Vond u de taken vergelijkbaar in hoe moeilijk het was de taak uit te voeren?
    a. Zo ja, leg alstublieft uit waarom
    b. Zo nee, welke vond u laster en leg alstublieft uit waarom

4. Had u in beide taken even veel het gevoel dat de ballen echt om u heen hingen?
    a. Zo ja, leg alstublieft uit waarom
    b. Zo nee, in welke voelde dit meer en leg alstublieft uit waarom

5. Leg alstublieft uit hoe het verschillende formaat van de Field of View uw ervaring beïnvloedde

6. Heeft u verder nog andere opmerkingen die u zou willen delen over uw ervaring?

Dit waren de vragen.

Hartelijk dank voor uw deelname!

12.2.2 Questionnaire Cooperation Test Headset Wearer

Wordt ingevuld door onderzoeker

Participant nummer:

Leeftijd:

Geslacht:

Volgorde bril:

- HoloLens 2 – Quest Pro
- Quest Pro – HoloLens 2

Volgorde levels:

- Level 1 – level 2
- Level 2 – level 1

Rol:

- Instructies
- Bom ontmantelen

Likert schaal

Na elke conditie zal u gevraagd worden om 17 vragen in te vullen aan de hand van een Likert Schaal zoals hieronder is weergegeven. Hierbij wordt een statement gegeven waarna u een hokje kan aankruisen in hoeverre u het eens bent met de stelling. Hierbij is 1 er totaal mee oneens zijn, 4 is neutraal/geen mening, en 7 volledig mee eens.

	1	**2**	**3**	**4**	**5**	**6**	**7**	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

Open vragen

Nadat u beide condities heeft getest zullen u nog 6 open vragen gesteld worden naar uw ervaring met de twee condities.

Likert Schaal Vragen Bom Ontmantelen

Kruis 1 hokje aan die het best overeenkomt met uw ervaring.

Samenwerking

1. We hadden goede samenwerking tijdens de taak

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

2. Ik voelde me gezien tijdens de taak

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

3. Ik keek mijn partner aan tijdens onze communicatie

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

4. Ik vond het fijn mijn partner te kunnen zien

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

5. Mijn partner kunnen zien bevorderde de samenwerking

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

6. Ik had het gevoel dat mijn partner begreep hoe ik me voelde

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

7. Ik begreep de instructies van mijn partner

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

Gebruikersgemak

8. Ik voelde me zelfverzekerd tijdens het gebruik van de HoloLens 2

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

9. Ik voelde me veilig tijdens het gebruik van de HoloLens 2

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

10. Ik voelde me gestrest tijdens de taak

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

11. Ik begreep hoe ik de HoloLens 2 moest gebruiken

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

12. Ik kon de virtuele content goed zien

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

13. Ik voelde me belemmerd in mijn bewegingsruimte

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

14. Ik wist hoe ver de virtuele content van me vandaan was

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

15. Ik was me bewust van objecten in mijn omgeving

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

16. Ik zou de HoloLens 2 ook aan anderen aanraden

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

Simulatieziekte

17. Geef aan in welke mate deze symptomen op het moment van toepassing zijn

	Niet	**Een beetje**	**Mild**	**Sterk aanwezig**
Hoofdpijn				
Vermoeide ogen				
Moeite met scherpstellen van beeld				
Misselijkheid				
Vol gevoel in uw hoofd				
Duizelig (met ogen open) (b.v., evenwicht verliezen, licht in het hoofd)				
Duizelig (met ogen dicht) (b.v., evenwicht verliezen, licht in het hoofd)				
Draaierig gevoel				

Open Vragen – Bom Ontmantelen

Beschrijf in uw eigen woorden hoe u de verschillende condities heeft ervaren naar aanleiding van de vragen.

1. Welke mixed reality ervaring had uw voorkeur?
    a. Leg alstublieft uit waarom

7. In welke bril had u de beste samenwerking?
    a. Leg alstublieft uit waarom

8. In welke bril had u het meeste het gevoel in controle te zijn?
    a. Leg alstublieft uit waarom

9. Beïnvloedde de mogelijkheid om de andere persoon direct aan te kijken de ervaring?
    a. Leg alstublieft uit waarom wel/niet

10. Welke headset vond u comfortabeler om te dragen en waarom?

11. Heeft u verder nog andere opmerkingen die u zou willen delen over uw ervaring?

Dit waren de vragen.

Hartelijk dank voor uw deelname!

12.2.3 Questionnaire Cooperation Test Instruction Giver

Wordt ingevuld door onderzoeker

Participant nummer:

Leeftijd:

Geslacht:

Volgorde bril:

- HoloLens 2 – Quest Pro
- Quest Pro – HoloLens 2

Volgorde levels:

- Level 1 – level 2
- Level 2 – level 1

Rol:

- Instructies
- Bom ontmantelen

Likert schaal

Na elke conditie zal u gevraagd worden om 9 vragen in te vullen aan de hand van een Likert Schaal zoals hieronder is weergegeven. Hierbij wordt een statement gegeven waarna u een hokje kan aankruisen in hoeverre u het eens bent met de stelling. Hierbij is 1 er totaal mee oneens zijn, 4 is neutraal/geen mening, en 7 volledig mee eens.

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

Open vragen

Nadat u beide condities heeft getest zullen u nog 5 open vragen gesteld worden naar uw ervaring met de twee condities.

Likert Schaal Vragen Instructies

Kruis 1 hokje aan die het best overeenkomt met uw ervaring.
Samenwerking

1. We hadden goede samenwerking tijdens de taak

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

2. Ik voelde me gezien tijdens de taak

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

3. Ik keek mijn partner aan tijdens onze communicatie

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

4. Ik vond het fijn mijn partner aan te kunnen kijken

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

5. Mijn partner kunnen aankijken bevorderde de samenwerking

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

6. Ik begreep hoe mijn partner zich voelde tijdens de taak

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

7. Mijn partner voelde zich gestrest

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

8. Ik had het gevoel dat mijn partner mijn instructies begreep

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

9. Ik voelde me gehoord door mijn partner

	1	2	3	4	5	6	7	
Ik ben het er helemaal niet mee eens								**Ik ben het er volledig mee eens**

Open Vragen - Instructies

Beschrijf in uw eigen woorden hoe u de verschillende condities heeft ervaren naar aanleiding van de vragen.

1. Welke mixed reality bril had uw voorkeur?
    a. Leg alstublieft uit waarom

2. Met welke bril had u de beste samenwerking?
    a. Leg alstublieft uit waarom

3. Beïnvloedde de mogelijkheid om de andere persoon direct aan te kijken de ervaring?
    a. Leg alstublieft uit waarom wel/niet

4. Verschilde de mogelijkheid om de anders stresslevels in te schatten afhankelijk van de bril?
    a. Leg alstublieft uit waarom wel/niet

5. Heeft u verder nog andere opmerkingen die u zou willen delen over uw ervaring?

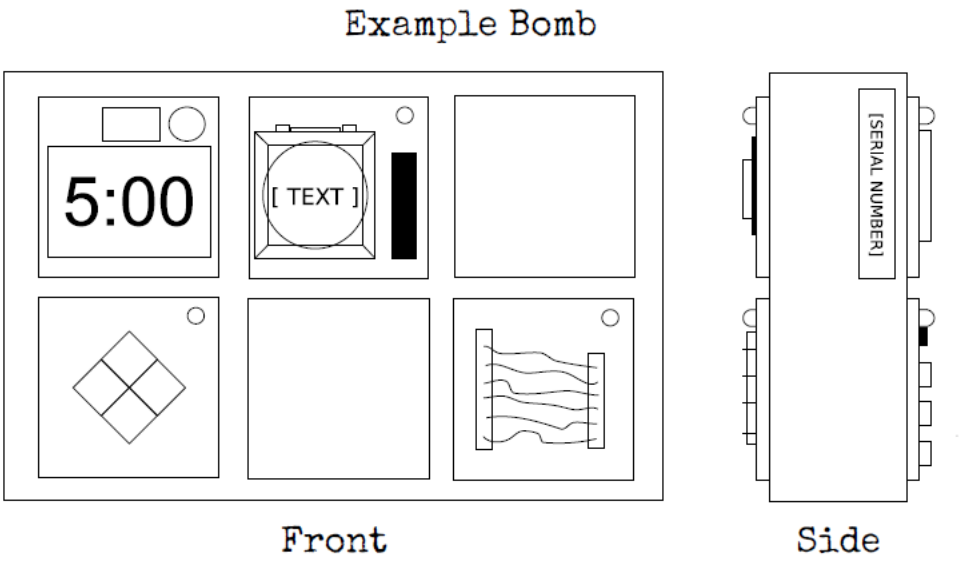
Dit waren de vragen.

Hartelijk dank voor uw deelname!

12.2.4 Instructions Provided During the Cooperation Test

Hoe ontmantel je een bom

Een bom explodeert als de countdown timer op 0:00 komt te staan of als er te veel fouten hebben plaatsgevonden. De enige manier om de bom te ontmantelen is door alle modules op te lossen voordat de tijd op is.



Modules

De bom zal een aantal modules bevatten die opgelost moeten worden. Ze kunnen in elke volgorde opgelost worden. Wanneer ze opgelost zijn zullen alle onderdelen of de zijkanten van een module groen oplichten.

Wanneer alle modules opgelost zijn en groen zijn opgelicht kan het de bom gestopt worden door op de groene knop te drukken boven op de bom.

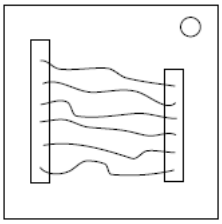
Levens

Als er een fout gemaakt wordt tijdens het oplossen van een module verliezen jullie een leven. In totaal hebben jullie 3 levens. Je levens worden geïndiceerd door drie groene bollen op de bom, wanneer jullie een leven verliezen zal een bol rood kleuren.

Informatie verzamelen

Sommige modules maken gebruik van specifieke informatie wat nodig is om ze op te lossen. Deze informatie is op de bom zelf te vinden zijn zoals op de zijkant of bovenkant.

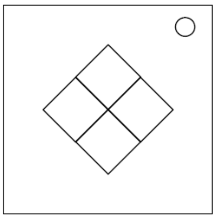
Draden



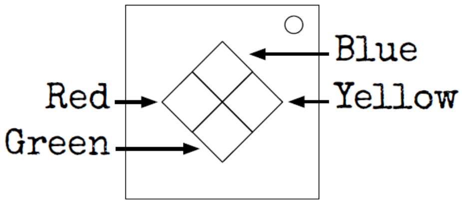
- Een module kan 3 – 6 draden bevatten
- Er is slechts een draad die doorgeknipt moet worden om te ontmantelen
- Een draad wordt doorgeknipt door aan te tikken
- De volgorde van draden begint met de eerste bovenaan

3 draden - Als er geen rode draden zijn, knip de 2e draad door - Anders, als het laatste draad wit is, knip de laatste draad door - Anders, als er meer dan 1 blauwe draden zijn, knip de laatste blauwe daad door - Anders, knip de laatste draad door
4 draden - Als er meer dan 1 rode draad is en het laatste getal van het serienummer is oneven, knip de laatste rode draad door - Anders, als de laatste draad geel is en er zijn geen rode draden, knip de eerste draad - Anders, als er precies 1 blauwe draad is, knip de eerste draad - Anders, als er meer dan 1 gele draad is, knip de laatste draad - Anders, knip de tweede draad
5 draden - Als de laatste draad roze is en het laatste getal van het serienummer is oneven, knip de vierde draad - Anders, als er precies 1 rode draad is en meer dan 1 gele draden, knip de eerste draad - Anders, als er geen roze draden zijn, knip de tweede draad - Anders, knip de eerste draad
6 draden - Als er geen gele draden zijn en het laatste getal van het serienummer is oneven, knip de derde draad - Anders, als er precies 1 gele draad is en er zijn meer dan 1 witte draden, knip de vierde draad - Anders, als er geen rode draden zijn, knip de laatste draad - Anders, knip de vierde draad

Simon says



- 1 van de 4 gekleurde vlakken gaat knipperen
- Gebruik de correcte tabel hieronder, druk op de knop met de corresponderende kleur
- De eerste knop gaat knipperen gevolgd door een ander, herhaal de serie in de juiste volgorde gebruik makend van de tabel
- De serie zal steeds langer worden met 1 vlak als de serie correct wordt uitgevoerd tot dat de module is ontmanteld



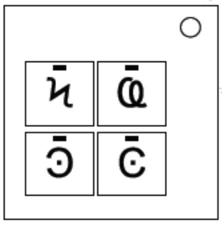
<u>Als het serienummer en klinker bevat</u>

		Red Flash	Blue Flash	Green Flash	Yellow Flash
Button to press:	**No Strikes**	Blue	Red	Yellow	Green
	1 Strike	Yellow	Green	Blue	Red
	2 Strikes	Green	Red	Yellow	Blue

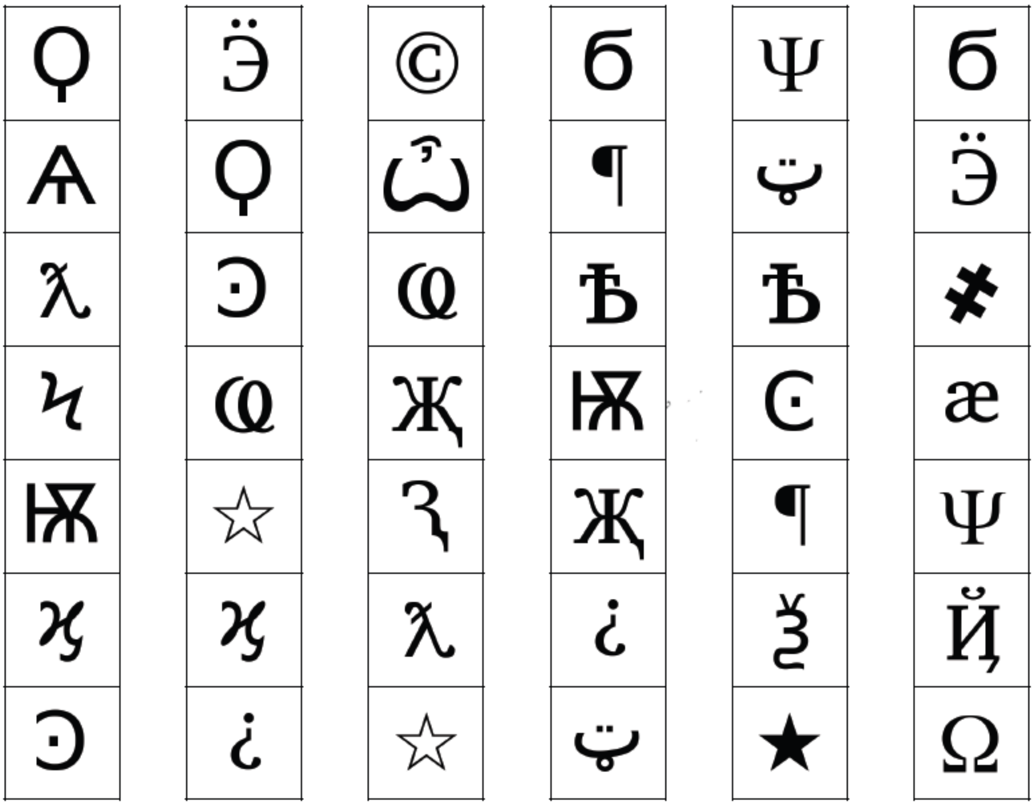
<u>Als het serienummer **geen** klinker bevat</u>

		Red Flash	Blue Flash	Green Flash	Yellow Flash
Button to press:	**No Strikes**	Blue	Yellow	Green	Red
	1 Strike	Red	Blue	Yellow	Green
	2 Strikes	Yellow	Green	Blue	Red

Keypads



- Hieronder staat slechts 1 kolom waar alle vier de symbolen die op de keypad staan zijn weergeven
- Druk de vier knoppen in de volgorde van hoe de symbolen weergegeven in de kolom van boven naar beneden



12.3 Questionnaire Used in the ABI Experience Test

Invullen door onderzoeker

Participant nummer:

Volgorde:

	HoloLens 2	Quest Pro	Quest Pro+redesign
1	○	○	○
2	○	○	○
3	○	○	○

Persoonlijke vragen (eenmalig aan het begin)

1. Wat is uw leeftijd?

2. Wat is uw geslacht/hoe identificeert u zich?

3. Wat is de oorzaak van uw hersenletsel?

4. Wanneer was het incident?

5. Welke kant is aangedaan?

6. Heeft u last van neglect of andere cognitieve problemen?

	Conditie:	Helemaal mee oneens	Oneens	Beetje oneens	Neutraal	Beetje eens	Eens	Helemaal mee eens
1.	Ik moest hard zoeken om de ballen te vinden							
2.	Ik had een goed overzicht van het spel							
3.	Ik kon de ballen makkelijk vinden							
4.	Ik was bewust van de objecten in mijn omgeving van de echte wereld							
5.	Ik kon me vrij beweging met de headset op							
6.	Mijn bewegingsvrijheid voelde gehinderd door de headset							
7.	Ik had het geval dat ik voorzichtig moest bewegen met de headset op							
8.	Ik voelde me veilig met de headset op							
9.	Ik voelde me zelfverzekerd tijdens het gebruiken van de headset							
10.	Ik kon makkelijk iemand om hulp vragen							
11.	Ik had het gevoel dat de onderzoeker/therapeut mij goed kon zien							
12.	Ik kon de virtuele objecten goed zien							
13.	Ik kon mijn omgeving (de echte wereld) goed zien							
14.	Het leek alsof de virtuele objecten echt om me heen hingen							

		Helemaal mee oneens	Oneens	Beetje oneens	Neutraal	Beetje eens	Eens	Helemaal mee eens
15.	Ik vond het fijn om de virtuele objecten en echte wereld tegelijkertijd te kunnen zien							
16.	Ik had moeite met door de headset kijken							
17.	Ik kon andere mensen goed zien							
18.	Ik kon goed focussen op het spel							
19.	Ik werd afgeleid door andere stimuli in de ruimte							
20.	De headset was comfortabel om te dragen							
21.	De headset was vermoeiend tijdens gebruik							
22.	De headset was makkelijk te gebruiken							
23.	Ik begreep hoe de headset werkte							
24.	Ik voelde me duizelig of licht in mijn hoofd tijdens of na het gebruik							
25.	Ik voelde me misselijk tijdens of na het gebruik							

Open vragen (eenmalig aan het einde)

1. Welke conditie had uw voorkeur? Waarom?

2. In welke conditie kon u het beste de virtuele content zien? En in welke de echte wereld? Wat vond u belangrijker om goed te kunnen zien en waarom?

3. In welke conditie had u het gevoel dat de virtuele objecten er echt waarom? Hoe kwam dat?

4. In welke conditie had u het gevoel het meest in controle te zijn? Hoe kwam dat?

5. Welke headset vond u het meest comfortabel om te dragen? Waarom?

6. Heeft u nog andere opmerkingen?

Dit is het einde van het onderzoek.

Hartelijk dank voor uw deelname aan dit onderzoek!