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# Enhancing Cultural Heritage Engagement Through Eye Gaze Locomotion in Virtual Reality

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# Preface

My introduction to this field was quite unplanned. Earlier in my studies, I happened to be at the right place to test various experiences created for the Nationaal Archief (Dutch National Archives) by fellow students. These experiences focused on Curaçao and the history of slavery, topics of great social relevance. Although these were less connected to traditional museum experiences and more focused on creating immersive interactions, they showed quite clearly how multimodal embodied experiences could effectively tell stories from the past. It was interesting to see how technology could make historical narratives more accessible and engaging for visitors.

After this testing session, discussions began about the opportunity to work on the Rembrandt House Museum project, which shared similar themes focused on emotions and representation. The practical application of immersive technology to cultural heritage seemed like a logical step forward from those initial experiences.

User studies in high schools provided valuable practical insight. Watching teenagers interact with the virtual exhibition, sometimes trying VR for the first time, offered direct feedback that theoretical research alone could not provide. Their reactions, both positive and negative, were instrumental in shaping this work.

Meeting the people who had created the original exhibition and seeing their interest in its virtual adaptation was motivating. Their attention to detail and commitment to telling these stories about representation provided an important context for technical implementation.

Although virtual reality was somewhat familiar territory, eye tracking technology was new ground. Working with this technology involved expected technical challenges, but also provided practical learning opportunities.

The guidance of my supervisors, the collaboration with the staff of the Rembrandt House Museum, and the input of all study participants was essential to this research. Thank you all.

Henrico Pops Enschede, June 2025

# Summary

Cultural heritage institutions are increasingly seeking ways to make their collections accessible and engaging for younger audiences. This research investigates how eye gaze-based locomotion methods might improve usability and presence in Immersive Virtual Reality (Immersive Virtual Reality (IVR)) exhibitions, using the HERE: Black in Rembrandt's Time exhibition as a case study. The exhibition presents Black individuals as central figures in 17th-century Dutch art, offering narratives about representation and diversity that could potentially resonate with adolescent visitors.

Preliminary studies with adolescents revealed significant challenges with traditional controller-based navigation in IVR. The participants struggled to understand the controls and became distracted by the technology itself rather than engaging with the exhibition content. These observations suggested that navigation barriers needed to be addressed before meaningful engagement with cultural narratives could occur.

This research examines whether eye gaze-based locomotion methods could provide more intuitive navigation, potentially allowing users to focus on exhibition content rather than interface mechanics. Two methods were developed and compared: direct eye gaze teleportation, where users instantly moved to locations they looked at, and eye gaze portal-based locomotion, where gazing at paintings generated portals that users physically walked through.

A within-subjects study with 29 participants (mainly university students aged 18-28) evaluated both methods using physical movement tracking, presence questionnaires (IGroup Presence Questionnaire (IPQ)), System Usability Scale (System Usability Scale (SUS)), and qualitative feedback. The eye gaze portal method was associated with more physical movement and higher spatial presence scores, while the teleportation method received slightly higher usability ratings.

In particular, participants using either eye gaze method spent considerably more time viewing artworks compared to data from previous studies using controller-based navigation (approximately 109-116 seconds versus 28 seconds in the first three minutes). Although this comparison involves different groups of participants and conditions, the magnitude of the difference suggests that removing distractions related to the controller may facilitate greater attention to the exhibition content.

The research also documented how participants maintained conventional museum behaviors in the virtual environment, standing at traditional viewing distances despite the freedom provided by virtual reality. This persistence of familiar behavioral patterns indicates that users apply existing mental frameworks even in novel technological contexts.

Both locomotion methods demonstrated acceptable usability levels, though neither proved universally superior. The optimal choice appears to depend on specific exhibition goals and user preferences. These findings establish the foundations for future research investigating whether improved navigation usability translates to increased appreciation of the diversity narratives presented in cultural heritage exhibitions. Although this study focused on the fundamental challenge of intuitive navigation, it represents the necessary foundation for examining more complex educational and cultural outcomes in subsequent research with adolescents.

# Contents

# List of acronyms

| | |
|---|---|
| **IVR** | Immersive Virtual Reality |
| **TCH** | Tangible Cultural Heritage |
| **HCI** | Human-Computer Interaction |
| **IPQ** | IGroup Presence Questionnaire |
| **SUS** | System Usability Scale |
| **SP** | Spatial Presence |
| **INV** | Involvement |
| **HMD** | Head-Mounted Display |

## Chapter 1

# Introduction

In recent years, Immersive Virtual Reality (IVR) technology has emerged as a powerful tool in various domains, including education, entertainment, and cultural heritage preservation [1], [2]. The integration of IVR into cultural heritage settings offers unique opportunities to transcend geographical and temporal boundaries, allowing users to experience historical artifacts and environments in immersive and interactive ways [3]. This technological advancement not only enhances user engagement but also has the potential to promote diversity awareness by presenting underrepresented perspectives in more accessible formats [4].

The Rembrandt House Museum's exhibition *HERE: Black in Rembrandt's Time* serves as a pivotal example of how cultural institutions are striving to highlight the contributions and representations of Black individuals in 17th-century Dutch art. By showcasing paintings and drawings where Black people are central figures rather than peripheral characters, the exhibition challenges historical stereotypes and promotes a more inclusive narrative.

Despite the potential of IVR in enhancing cultural heritage experiences, there remain challenges to effectively engage younger audiences, particularly adolescents. [4]

## 1.1 Problem statement

Current IVR exhibitions often rely on traditional hand-held controllers for navigation and interaction, which can present usability challenges for adolescents unfamiliar with such devices [4]. Preliminary studies have shown that adolescents can become preoccupied with the mechanics of technology rather than the narratives and educational material presented, leading to decreased engagement [5]. These usability issues can hinder the effectiveness of IVR exhibitions in promoting awareness of diversity and cultural appreciation. If adolescents cannot seamlessly interact with the virtual environment, the potential educational benefits and the impact of the exhibition's message may be diminished.

## 1.2 Research objectives

The primary objective of this research is to investigate how replacing traditional handheld controllers with gaze-based eye interactions, particularly for locomotion methods, in an IVR cultural heritage exhibition can improve usability and presence, which could potentially improve adolescents' appreciation of diversity in art, although this particular investigation remains outside of the scope of this research. The specific objectives are as follows. First, the research aims to enhance usability by designing eye gaze-based locomotion methods that are intuitive for adolescents, thereby reducing the onboarding needs for explaining interaction mechanics associated with traditional controller-based navigation systems. Second, the study seeks to increase presence and engagement by encouraging greater physical movement and more behavioral engagement with the artworks through simplified locomotion and interaction methods that allow users to focus on exhibition content rather than navigation mechanics. Third, the research aims to establish a foundational understanding of how different eye gaze-based locomotion approaches influence the sense of being present within virtual cultural heritage spaces, as presence may contribute to more meaningful engagement with exhibition content.

## 1.3 Research questions

This research is guided by the following research questions:

**Main research question:** "How can eye gaze-based locomotion methods enhance adolescent engagement with immersive virtual cultural heritage exhibitions?"
**Sub-questions:**

1. What eye gaze-based locomotion designs are most intuitive and usable for young people in virtual exhibition environments?"

2. How does eye gaze-based locomotion influence physical movement and presence experience in virtual cultural heritage spaces?"

3. "To what extent does eye gaze-based locomotion usability affect young people's viewing time behaviors with virtual artworks in IVR?"

By focusing on locomotion usability and presence, this research establishes foundations for effective virtual cultural heritage experiences. When users can navigate intuitively and feel genuinely present in the virtual environment, they are more likely to engage deeply with exhibition content rather than struggling with technical barriers. This enhanced engagement could potentially amplify the intended impact of the exhibition, allowing powerful narratives about diversity and representation in historical art to reach adolescents more effectively.

## Chapter 2

# Context & related work

This chapter explores relevant literature and developments in the intersection of Immersive Virtual Reality (IVR), cultural heritage education, and diversity representation. An overview is provided of how these fields connect and influence each other, with specific focus on interaction methods that could enhance engagement. Current challenges in IVR implementation for cultural heritage contexts are examined, along with potential solutions through eye gaze-based interaction. The exhibition "HERE: Black in Rembrandt's Time" is presented as a case study for researching how improved interaction methods might enhance appreciation of diversity narratives in art. Through this literature review, gaps are identified that this research aims to address.

The digital transformation of cultural heritage experiences has created new possibilities to make art and history more accessible and engaging, particularly for younger audiences. In this context, *HERE: Black in Rembrandt's Time* exhibition at the Rembrandt House Museum serves as a case study to explore how IVR can not only preserve cultural heritage but also improve appreciation of diversity in art through improved interaction methods.

The representation of marginalized groups in art has historically been limited, with individuals of color often depicted in stereotypical roles or as peripheral figures rather than as central subjects with agency and individuality. As noted in the exhibition documentation, black people were frequently portrayed "not simply as secondary figures in subordinate roles, but often the subjects of the work" during Rembrandt's time, before later stereotypes became more prevalent [6]. In recent years, museums have begun to critically examine their collections and narratives, working to highlight overlooked perspectives and promote more inclusive understandings of history. The *HERE: Black in Rembrandt's Time* exhibition represents such an effort, bringing attention to the presence and significance of Black individuals in 17th-century Dutch art. The exhibition challenged visitors to recognize that "black people were present in the Netherlands in the seventeenth century" and were part of Rembrandt's neighborhood around Jodenbreestraat [6]. By digitally recreating this exhibition in IVR, there appears to be an opportunity to extend its reach and potentially enhance its impact, particularly among adolescents who may engage differently with digital experiences than with traditional museum visits.

The capacity of IVR to create emotionally resonant experiences makes it particularly suitable for exhibitions focused on diversity and representation. Studies suggest that virtual galleries can effectively replicate the experience of physical galleries, offering an ecologically valid environment for cultural exploration [3]. As Freedberg et al. [7] argue, engagement with art involves not just cognitive processing, but also embodied simulation mechanisms that allow viewers to emotionally connect with what is depicted. However, realizing this potential requires addressing significant usability challenges, particularly those related to navigation and interaction within virtual environments.

### 2.0.1 HERE: Black in Rembrandt's Time

The exhibition 'HERE: Black in Rembrandt's Time' at the Rembrandt House Museum examined Black people in Dutch art from the 17th century, running from March 6 to May 31, 2020 [6]. The exhibition challenged conventional narratives by demonstrating that Black individuals appeared in art between 1620 and 1660 in diverse roles, countering the typical representation of black people in visual arts as dehumanizing and stereotypical [6].

The exhibition's layout strategically presented these contrasting narratives, with sections dedicated to examining both stereotypes and respectful portrayals (Figure 2.1). This spatial arrangement guided visitors through a complex historical narrative that distinguished between different periods of representation. Later artistic representations would become dominated by harmful stereotypes that emerged to justify the transatlantic slave trade. As documented in the exhibition, these stereotypes portrayed Black people as "exotic savages" and emphasized their supposed "natural inclination to slavishness," serving to rationalize the inhuman treatment of enslaved people [6]. However, during Rembrandt's time, "the stereotypes that later fixed the image of black people were yet to prevail" [6].

Several factors contributed to the emergence of non-stereotypical Black portrayals during Rembrandt's period. First, artists like Rembrandt were committed to "working 'from life'" and "painting from life," which meant they created direct studies of Black people in various media including ink, chalk, paint, and clay [6]. These works captured spontaneous observations of the people around them. Second, a small but significant Black community existed in Amsterdam during the 17th century. Research revealed that "there was a small community of free black people around Jodenbreestraat, in Rembrandt's neighbourhood" between around 1630 and


**Figure 2.1:** An overview of the 'Stereotypes' and 'Black from a Distance' sections in the exhibition, showing how spatial arrangement and thematic organization guide visitor understanding and engagement with the artworks. The physical layout of the exhibition influences how visitors encounter and interpret the narratives presented.

1660 [6]. These residents included sailors from Africa or Brazil and servants who came with Portuguese Jewish immigrants, making them a visible part of local society. Third, although the Dutch were becoming involved in the transatlantic slave trade during this period, particularly in Brazil, this involvement was not yet widely known in Amsterdam. Consequently, artistic representations remained relatively neutral and respectful, depicting Black individuals in various roles including biblical and classical scenes.

The exhibition's presentation of individual portraits emphasized this dignified representation (Figure 2.2), showcasing works where Black subjects were given visual prominence typically reserved for important figures in society. The exhibition highlighted "tronies" - character studies of faces or heads that were often enhanced with exotic costumes and accessories. Black people served as models for these tronies, being "portrayed as individuals at the center of attention" rather than as peripheral figures [6]. The exhibition also featured contemporary Black artists reflecting on their heritage and identity, connecting historical representation with modern perspectives [6].

As part of the nationwide initiative "Musea Bekennen Kleur" ("Museums Confess Color"), involving at least 45 participating museums[1], the exhibition contributed to a broader movement promoting diversity and inclusivity in cultural institutions. By highlighting these overlooked artistic works, the Rembrandt House Museum challenged visitors to reconsider established narratives and recognize the complexity of

[1] https://museabekennenkleur.nl/

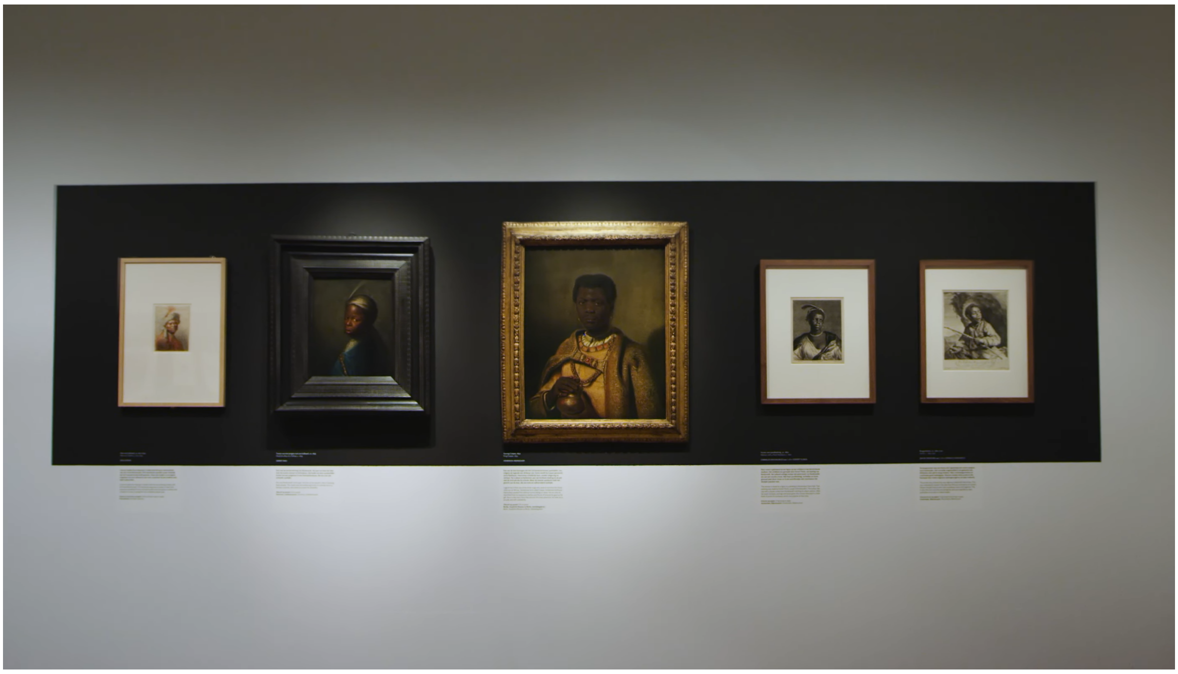

**Figure 2.2:** A section showcasing portraits of Black individuals in 17th-century Dutch art.

Black presence in Dutch society.

## 2.1 Enhancing cultural heritage through IVR

IVR offers unique opportunities to transform how cultural heritage is experienced and understood. By enabling virtual visits to historical sites and artifacts, IVR transcends physical and temporal boundaries, creating new possibilities for engagement and learning [1], [3]. However, the effectiveness of these experiences depends significantly on the design of interaction methods, which must balance usability, engagement, and educational value.

### 2.1.1 Potential benefits and critical challenges

The integration of IVR into cultural heritage education offers several potential advantages, though each comes with important limitations that must be addressed:

**Accessibility and preservation** IVR can democratize access to cultural heritage by making collections and sites available to global audiences regardless of physical location [4]. Digital preservation also protects artifacts from physical deterioration and damage. However, a critical examination reveals that digital experiences often lack the authenticity and contextual richness of physical encounters with heritage objects. As Marto et al. [8] note, the sensory limitations of current IVR technology can diminish the multisensory dimensions of cultural heritage experiences. Furthermore, accessibility remains constrained by the digital divide, with advanced IVR technology still unavailable to many populations.

**Immersive learning** By transforming passive observation into active participation, IVR can engage multiple senses and facilitate deeper cognitive processing [1], [2]. The immersive nature of IVR allows learners to explore and interact with cultural artifacts in novel ways, potentially enhancing memory retention and educational outcomes. However, studies have shown mixed results on the educational effectiveness of IVR compared to traditional learning methods. Kabassi and Maravelakis [9] found that while IVR can increase initial engagement, this engagement does not always translate to deeper understanding or retention of information. The novelty effect may temporarily boost interest without sustaining long-term learning benefits.

**Diversity and representation** IVR offers opportunities to present underrepresented perspectives and challenge traditional historical narratives [4]. By highlighting the contributions and experiences of marginalized groups, IVR can potentially foster greater cultural understanding and inclusivity. Yet, as with any medium, IVR experiences are not neutral; they reflect the perspectives, priorities, and potential biases of their creators. Critical examination of who designs these experiences and whose voices they amplify remains essential. Furthermore, the relationship between technological immersion and actual changes in attitude or appreciation regarding diversity has not been thoroughly established in the literature. The implementation of IVR in cultural heritage settings faces several significant challenges that impact user experience and engagement:

**Technical and design limitations** Effective IVR systems for Tangible Cultural Heritage (Tangible Cultural Heritage (TCH)) require careful design, particularly with respect to system controls, navigation, and user interactions [4], [10]. The lack of standardized interaction mechanisms and limitations on movement can conflict with users' real-world expectations, leading to confusion and decreased engagement. A study by Sun et al. [5] found that over 86% of participants encountered situations where they were unable to proceed in an IVR cultural heritage experience due to insufficient guidance or unclear interaction mechanisms. This highlights a critical gap between the potential of IVR technology and its practical implementation.

**Navigation and spatial awareness** Navigation within virtual environments represents a particularly challenging aspect of IVR experiences. Common methods like teleportation can negatively affect the user's sense of presence and spatial awareness [9]. Users often experience difficulty understanding spatial relationships and distances, sometimes leading to disorientation or even vertigo [5]. These issues can significantly reduce the overall experience and educational value of IVR cultural heritage applications.

**Usability for diverse audiences** Usability challenges are especially pronounced among younger users or those unfamiliar with IVR technology [4]. Traditional handheld controllers can be confusing or distracting for adolescents, potentially limiting their engagement with the exhibition content. This presents a particular concern for educational applications targeting younger audiences, as technological barriers can prevent meaningful engagement with cultural content. Although some studies suggest that younger generations adapt quickly to new technologies, the research by Bailey and Bailenson [11] indicates that young people can process virtual environments differently than adults, which requires specially designed interaction methods.

These challenges highlight the need for innovative approaches to interaction design in IVR cultural heritage applications. Eye gaze-based interactions emerge as a promising alternative that may address many of these issues, potentially creating more intuitive, engaging, and accessible experiences for diverse audiences.

## 2.2 Eye-gaze interactions: Potential and Limitations for Cultural Heritage IVR

Eye gaze-based interactions offer a potentially more natural and intuitive way to navigate and interact within virtual environments, addressing many of the challenges associated with traditional controller-based methods. Using the natural tendency of humans to look at objects of interest before interacting with them, eye gaze interactions could reduce cognitive load and create more seamless experiences [12], [13].

### 2.2.1 Engagement with art

Understanding how users engage with artworks is crucial for designing effective interaction methods in cultural heritage IVR. Research in neuroaesthetics provides valuable information on this process. Freedberg and Gallese [7] propose that viewer responses to art involve embodied simulation mechanisms that enable them to internally replicate the emotions and actions depicted in the artworks. This process facilitates deeper empathetic connections with the content.

Kesner and Horáek [14] further elaborate that art engagement involves a complex interaction between the characteristics of the artwork, the personal factors of the viewer and contextual elements. They suggest that prolonged interaction with artworks creates a cyclical reinforcement between emotional engagement and aesthetic appreciation, as illustrated in Figure 5.1.

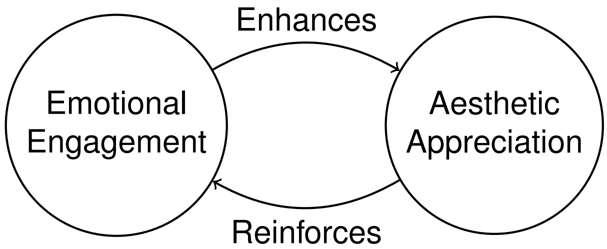


**Figure 2.3:** Cyclical reinforcement between emotional engagement and aesthetic appreciation during prolonged interaction with art [14].

This model has significant implications for IVR design. If eye gaze-based interactions can facilitate more comfortable and extended emotional engagement with artworks, they might enable the cyclical reinforcement process described by Kesner and Horáek, potentially leading to deeper appreciation of the artwork's content, including themes of diversity and representation. However, Kesner [15] notes that contemporary viewers often interact with artworks too briefly for deep emotional processing to occur. This suggests that interaction design could explicitly encourage sustained attention to maximize engagement with diversity themes.

The potential application of eye tracking in cultural heritage settings has evolved from the initial analysis of visitor behavior [16] to more interactive applications. Studies by Villani et al. [17] and Calandra et al. [18] examined how eye tracking can reveal visitor cognitive processes and emotional reactions to art. Based on this research, Dondi and Porta [19] suggest that eye gaze can be used not only for analysis, but also as an interaction modality to enhance the natural and engaging aspects of experiencing art.

### 2.2.2 Technical approaches

Several approaches to eye gaze interaction have been explored in the literature, each with distinct advantages and limitations:

**Dwell time vs. gaze gestures** Two primary techniques for eye gaze input are dwell time and gaze gestures [19]. Dwell time requires users to fixate on a target element for a predetermined duration to activate an action. This approach is relatively intuitive, but must be carefully calibrated to avoid the 'Midas touch problem' [20], where unintended actions are triggered by natural looking behavior. Gaze gestures involve specific eye movement patterns to execute actions. Although these are less prone to accidental activation, they have a steeper learning curve and may be less suitable for first-time or occasional users; this could be an important consideration for museum applications.

**Hands-free teleportation studies** Research comparing various hands-free teleportation methods offers valuable information for cultural heritage applications. Prithul et al. [21] conducted a study with 20 participants comparing dwell time, eye wink, mouth gesture, and traditional controller-based teleportation. While eye wink teleportation matched controllers in efficiency, dwell time required fewer attempts for successful selection and resulted in fewer errors. Interestingly, despite the novelty of eye-based methods, participants still showed a preference for the tactile feedback provided by controllers. This suggests that eye gaze interactions, while promising, may face acceptance challenges that need to be addressed through careful design and user familiarization.

**Augmented navigation with eye tracking** Eye tracking can enhance other navigation techniques, such as redirected walking. By subtle adjustment of the view during eye blinks [22] or saccades [23], systems can create more natural-feeling movement while working within constraints of physical space. Techniques utilizing inattentional blindness and foveated rendering can apply spatial transformations based on the importance of the scene [24]. These approaches could be particularly valuable for cultural heritage applications, where space constraints in physical exhibition environments might limit the possibilities for movement.

**Eye gaze navigation techniques** Eye gaze-based navigation commonly uses the point-and-fly method, where users direct their gaze toward a destination to initiate movement [25]. Variations include orbital navigation, which allows users to rotate objects according to their eye gaze to maintain them in view [26], [27]. These approaches show potential for cultural heritage applications, where you could keep the viewer engaged longer. However, research by Al Zayer et al. [28] indicates that navigation techniques impact the sense of presence and spatial understanding of users, suggesting that eye gaze navigation methods must be carefully evaluated in the specific context of cultural heritage exhibitions. Therefore, this will be at the center of this thesis.

### 2.2.3 Immersion and presence

Immersion and presence are critical factors in evaluating the effectiveness of IVR experiences. Although sometimes used interchangeably, these terms have different definitions in the HMI field. For this study, the following definitions are used.

**Immersion** refers to the objective technological aspects of the IVR system, such as visual fidelity, interactivity, and sensory stimuli, which contribute to creating a believable virtual environment. On the other hand, **presence** is the subjective psychological sensation of 'being there' within this virtual environment, strongly influencing user engagement, emotional responses, and learning outcomes [8].

**Physical movement and presence** Recent research has established a significant positive correlation between user-initiated motion and self-reported presence in IVR environments [29]. Using high-frequency tracking, studies have visualized clear differences in movement patterns between participants with high-motion and low-motion. Importantly, increased physical movement has not been associated with higher rates of motion sickness, suggesting that interaction methods that encourage movement could improve presence without negative side effects. This finding has important implications for the design of eye gaze locomotion systems, suggesting that approaches that facilitate natural physical movement may enhance overall engagement with cultural content.

Commonly used measurement tools for presence include:

- **Presence Questionnaire (PQ)** [30]: Widely used to assess presence through subjective evaluations, covering dimensions like "Involvement, Adaptation/Immersion, Sensory Fidelity, and Interface Quality."
- **Immersive Tendencies Questionnaire (ITQ)** [31]: Measures individual differences in the tendency to experience presence, developed alongside the PQ to account for personal factors that influence immersion in virtual environments.
- **Slater-Usoh-Steed (SUS) Questionnaire** [32] [33]: Specifically, it measures the subjective depth of presence experienced by users.
- **IGroup Presence Questionnaire (IPQ)** [34], [35]: Evaluates presence in four dimensions: spatial presence, involvement, realism, and general presence, providing a detailed understanding of the psychological experience of the user.

Despite the availability of these tools, the subjective nature of presence and immersion and potential novelty effects associated with IVR, particularly among adolescents, pose challenges in measurement [36].

### 2.2.4 Addressing the specific needs of adolescent users

Adolescents represent a significant but often overlooked user group for cultural heritage IVR applications. The design of eye gaze interactions for this demographic must consider their unique characteristics, preferences, and challenges:

**Developmental considerations** IVR experiences targeted at adolescents must account for developmental factors that influence how they perceive and interact with virtual environments. Bailey and Bailenson [11] note that younger users may experience more intense immersion in virtual reality compared to adults, but may also face challenges in distinguishing between virtual and physical realities, a phenomenon known as the "dual representation" problem. This suggests that eye gaze interactions for adolescents should provide clear visual feedback to help users maintain awareness of the interaction system while remaining immersed in the content.

**Exploratory behavior patterns** Studies of adolescents in virtual environments reveal distinctive interaction patterns characterized by exploratory, sensory-driven behaviors [37]. Adolescents often attempt to interact with virtual objects in ways that mimic real-world behaviors, suggesting that natural interaction methods like eye gaze could align well with their intuitive approaches. However, this exploratory tendency also means that interaction systems must be robust against accidental activations and clearly communicate interaction possibilities to channel this exploratory energy productively.

**Attention and cognitive load** Reducing the cognitive load is particularly important for adolescents, who may have less capacity to manage complex interaction systems while simultaneously engaging in educational content. Eye gaze interactions have the potential to reduce this cognitive burden by eliminating the need to learn controller-based input methods, potentially allowing greater attention to be directed toward the exhibition content [12]. However, this benefit can only be realized if the eye gaze interactions themselves are designed to be sufficiently intuitive and unobtrusive.

**Evaluation considerations** Assessing the effectiveness of eye gaze interactions among adolescents requires specialized approaches. Traditional self-report measures may not fully capture the experience of adolescents due to developmental differences in self-expression and reflection [11]. A more comprehensive evaluation approach might combine observation-based methodologies focused on body movements and behaviors with physiological metrics such as heart rate and eye movement patterns [38]. These objective measures can provide information on emotional and cognitive responses that participants may not be able to articulate through conventional self-report measures.

## 2.3 Implications for current research

The literature reveals a significant gap in understanding how eye gaze-based interactions can address specific usability challenges in cultural heritage IVR applications for adolescents. Although existing research demonstrates the potential of eye gaze interaction in general VR contexts, limited research has been conducted on its application to cultural heritage exhibitions.

Within this broader domain, the current study focuses specifically on eye gaze-based locomotion as a foundational element that must be established before investigating complex educational outcomes. This research examines usability and presence as more comprehensive indicators of successful interaction design. Usability reveals whether the interface becomes sufficiently transparent for users to focus on content rather than controls, while presence indicates the quality of immersive experience that enables engagement with cultural narratives. As detailed in the following chapter on preliminary studies, observations of existing controller-based systems revealed specific navigation difficulties and interface distractions that also informed the direction toward eye gaze locomotion methods.

The *HERE: Black in Rembrandt's Time* exhibition provides an ideal context for examining how different locomotion modalities affect user experience, establishing groundwork for future studies on the relationship between interaction design and the engagement with the artworks.

# Chapter 3

# Preliminary Studies

To gain preliminary insights and guide the research direction, we used observations of two user studies with the IVR exhibition of *HERE: Black in Rembrandt's Time*. These studies aimed to observe how adolescents interact with the IVR environment and identify usability challenges that could inform the development of eye gaze-based interactions.

## 3.1 First user study observations

The first user study involved 23 participants, consisting of 21 high school students taking an elective course in computer science and 2 teachers. The study was carried out at their high school, where two IVR setups were installed, allowing the simultaneous participation of two individuals. The IVR experience presented a digital twin of the exhibition, developed using Unity and accessed via the HTC VIVE Pro Eye headset. Participants were given a brief introduction on how to navigate using handheld controllers and were then allowed to explore the virtual exhibition at their own pace.

Observations made during the study were insightful. These observations are crucial in understanding the user experience and potential areas for improvement in IVR applications, especially in educational settings.

### 3.1.1 Key findings preliminary study 1

Several observations were made during the study.

- **Excitement about technology**: Many participants expressed enthusiasm about using IVR technology, with some experiencing it for the first time. This excitement suggests a strong initial engagement due to the novelty effect [36].
- **Impressed by visual quality**: The participants were impressed with the realistic visuals and high-quality rendering of the virtual environment, indicating that the digital twin effectively captured the details of the physical exhibition.
- **Navigation challenges**: A common struggle among participants was navigating the virtual space using handheld controllers. Those unfamiliar with IVR technology found it difficult to maneuver, which sometimes led to frustration and decreased engagement. In particular, this observation contributed greatly to the starting point of this thesis.
- **Limited physical movement**: The participants exhibited minimal physical movement within the play area. This could be attributed to fear of colliding with physical objects, discomfort from not being able to see the real world, or constraints imposed by the headset's tethered connection.
- **Fascination with virtual hands**: Many participants were intrigued by the virtual representation of their hands, spending time manipulating and observing them rather than engaging with the exhibition content.
- **Attempts to interact with artwork**: Some participants tried to physically interact with the virtual artwork, such as trying to grab or remove paintings from the walls, suggesting an expectation of interactivity that was not met.
- **Exploring virtual boundaries**: Participants exhibited curiosity about the limits of the virtual environment, such as walking through walls or placing their heads inside virtual objects.
- **Distracting teleportation laser**: The teleportation laser used for navigation was often a distraction. The participants frequently pointed it at random objects or their own faces, indicating that the navigation tool drew attention away from the exhibition content.

## 3.2 Second User Study Observations

The second user study involved a new group of adolescents who interacted with an interactive version of the IVR exhibition. This version was developed within the social IVR platform Resonite [1] and was an extension of an earlier project. [39] This

[1] https://resonite.com/

included interactive elements such as a puzzle where participants could manipulate virtual objects related to the artworks. Similarly to the first study, participants were given a brief introduction on using the controllers, with additional instructions on how to interact with the virtual objects.

The following observations were made during the second user study. For the interactive version, a similar short onboarding was used, but there was an extra mention of the 'grab' button and that instructions were visible within the visit. Most of the previously mentioned observations were also noticed. The following observations are additional observations based on new observations from the interactive version.

### 3.2.1 Key findings preliminary study 2

Additional observations from this study included the following.

- **Ignoring instructions**: Many participants did not read the instructions on screen provided within the virtual environment. This led to confusion about how to interact with the interactive elements and suggests the need for more intuitive onboarding processes [40].
- **Lack of interaction with interactive elements**: Most of the participants did not engage with the interactive features as intended. This may indicate that the interactions were not sufficiently intuitive or that participants were unsure how to proceed without explicit guidance.
- **Incomplete puzzles**: Participants who started to interact with the puzzle elements often did not complete the tasks. This suggests that the activities may not have been sufficiently engaging or too complex.
- **Usability and technical issues**: Some participants encountered technical problems, such as teleporting into walls, grabbing multiple objects simultaneously, triggering multiple overlapping audio dialogues, and being unable to reach certain interactive elements. These issues likely hindered the overall user experience and engagement, highlighting the critical importance of interaction design in determining whether users can focus on cultural content rather than struggling with technology itself.

- **Continued navigation challenges**: Similarly to the first study, participants struggled with navigation using handheld controllers, reinforcing the need for more intuitive navigation methods.

- **Distractions from controllers**: The participants remained fascinated by the controllers and virtual representations of their hands, which continued to distract them from fully engaging with the exhibition content.

## 3.3 Implications for current research

The observations of both user studies highlight several challenges in the current IVR exhibition that need to be addressed to improve usability and engagement among adolescents.

### 3.3.1 Need for improved locomotion

The consistent navigation challenges indicate that the traditional controller-based teleportation system is not sufficiently intuitive for adolescents unfamiliar with IVR technology. Participants' struggles with movement and spatial orientation within the virtual environment suggest that these issues detract from their ability to engage with the exhibition content. Eye gaze-based locomotion offers a promising alternative, potentially providing a more natural and intuitive method for navigation [25]. By allowing users to move through the virtual space using their gaze direction, the cognitive load associated with controller operation could be reduced, enhancing immersion and focus on the artworks.

### 3.3.2 Simplifying interactions

The lack of engagement with interactive elements and the tendency to ignore instructions highlight the importance of simplifying interactions within the IVR environment. Adolescents may be less inclined to read detailed instructions or may find complex interaction mechanisms discouraging. Implementing eye gaze-based interactions can simplify the user experience by reducing reliance on controllers and making interactions more intuitive [12]. By designing interactions that align with natural gaze behaviors, users may find it easier to engage with the content, leading to increased emotional connection and appreciation of the exhibition themes. However, the investigation of broader interactive elements beyond locomotion falls outside the scope of this thesis. The current research focuses specifically on eye gaze-based locomotion as a foundational step in addressing the core navigation barriers identified in preliminary studies.

### 3.3.3 Minimizing distractions

The fascination with virtual hands and controllers suggests that these elements can distract attention away from the exhibition content. By eliminating the need for hand-held controllers through eye gaze-based interactions, it is possible to minimize these distractions. This could help users focus more on the artworks and their narratives, enhancing emotional engagement, and the overall effectiveness of the exhibition in promoting diversity awareness. In the current research, hand-held controllers are therefore omitted from the designed interaction methods. This approach allows for direct investigation of whether eye gaze-based locomotion can reduce interface-related distractions and enable greater attention to be directed toward the cultural content itself.

### 3.3.4 Enhancing user engagement with artworks

Participants' attempts to interact physically with the virtual artworks indicate a desire for more engaging and interactive experiences. Incorporating gaze-based interaction can facilitate more meaningful interaction with the artworks by allowing users to interact with them intuitively, such as triggering additional information or animations when looking at specific elements [19]. This approach can deepen users' emotional connection to the art and enhance their understanding of the historical and cultural contexts.

### 3.3.5 Conclusion from preliminary studies

Preliminary studies underscore the need to rethink interaction paradigms within the IVR exhibition to better suit adolescent users. In this study, the identified challenge of controller-based navigation difficulties is first addressed through the implementation of eye gaze-based locomotion. This foundational approach aims to enhance usability and immersion first, which are considered prerequisites for meaningful engagement with exhibition content. By removing the barriers associated with understanding controllers and reducing the onboarding needs for explaining interaction mechanics, a more accessible experience may be created. This strategic focus on interaction design establishes the groundwork for the overarching goal of promoting adolescents' appreciation of diversity in art through more intuitive and immersive virtual museum experiences.

# Chapter 4

# Designing IVR eye-gaze locomotion

Building on the findings of our preliminary studies, this chapter outlines the process of designing locomotion methods that could potentially improve user engagement in IVR cultural heritage settings. The goal is to address the identified issues with traditional controller-based navigation while creating eye gaze-based locomotion methods that allow users to focus on the exhibition content rather than learning navigation controls.

## 4.1 Design Principles for locomotion

The design of an effective locomotion system is crucial for ensuring that users can navigate the IVR exhibition intuitively and comfortably, which directly impacts their engagement and immersion. Based on our preliminary studies, we identified several fundamental issues with controller-based locomotion that needed to be addressed through thoughtful redesign.

### 4.1.1 Locomotion design goals

Based on the identified challenges, we established the following goals for our locomotion system design:

1. **Intuitive navigation**: Create an interaction paradigm that feels natural and requires minimal explanation or learning, particularly for adolescents who may be new to IVR experiences.

2. **Encouraging physical movement**: Design a system that motivates users to physically move within the available space, which can improve presence. [29].

3. **Reducing controller dependency**: Minimize or eliminate the need for handheld controllers, allowing users to interact more naturally with the virtual envi-

ronment.

4. **Maintaining low motion sickness**: Ensure that the locomotion method does not induce discomfort or nausea, which can severely impact the user experience [41].

5. **Optimizing room-scale utilization**: Leverage the available physical space to encourage meaningful physical movement without requiring navigation patterns that exceed the boundaries of a typical VR setup. (approximately 2.52m × 3.94m in our lab studies)

6. **Avoiding room modifications**: Design a solution that works within existing physical constraints without requiring modifications to the testing environment, such as additional physical props, boundary walls, or specialized room configurations needed for impossible space techniques.

These goals guided our exploration of alternative locomotion methods, with a particular focus on techniques that could leverage eye tracking capabilities already present in our VR hardware.

## 4.2 Exploring Locomotion Alternatives

To identify potential solutions, we explored various locomotion techniques documented in existing literature and evaluated them against our design goals.

### 4.2.1 Evaluation of existing techniques

Several established locomotion methods were considered:

**Redirected walking** This technique subtly manipulates the virtual environment to allow users to walk infinitely within a finite physical space [28], [42]. While this method maximizes physical movement and eliminates controllers, it requires sophisticated real-time environment manipulation and potentially larger physical spaces than available for our study.

**NaviFields** This approach varies movement amplification based on the importance of different areas in the virtual environment [43]. While interesting, this method might be more complex to implement and could potentially cause disorientation for inexperienced users.

**Eye-gaze based locomotion** This technique enables hands-free teleportation by using head gaze for destination selection and dwell time for activation. Prithul et al. [21] evaluated this approach along with other hands-free methods (eye-wink and mouth gesture), finding that dwell-based eye-gaze teleportation offered comparable performance to controller-based methods while eliminating the need for hand controllers. The method requires users to fixate their gaze on a target location for a predetermined duration (typically 1-2 seconds) to activate teleportation, making it accessible for users with limited hand mobility while requiring only eye tracking capabilities.

**Waypoints navigation (Teleport presets)** This approach places predetermined teleportation points within the virtual environment, which users can activate to instantly move to that location. When combined with eye tracking, users could activate waypoints by gazing at them for a predetermined dwell time [44]. This method aligns with our goals of intuitive use and controller independence, while potentially encouraging some physical movement within each waypoint area.

**Portal-based navigation** Portal systems create visible connections between different areas of the virtual environment, allowing users to move between them by physically walking through the portal [45]. When combined with eye tracking, this could provide a novel approach where users generate portals by gazing at destinations. This might encourage physical movement while maintaining a clear connection between different spaces in the exhibition.

### 4.2.2 Selection of methods for comparative study

After evaluating various techniques against our design goals, we identified two promising eye gaze-based methods for further investigation:

- **Eye gaze teleportation**: A straightforward implementation where users look at the floor area in front of a painting, and after a one-second dwell time, they are instantly teleported to that location. This method leverages natural gaze behaviors and eliminates controllers while being relatively simple to implement.

- **Eye gaze portal navigation**: A more innovative approach where gazing at a painting for one second generates a portal connecting the user's current position to the area in front of the painting. Users must then physically walk through the portal to reach the new location, potentially encouraging greater physical movement.

Both methods eliminate the need for hand-held controllers, potentially addressing many of the issues identified in our preliminary studies. However, they differ significantly in how they handle the actual transition between locations, with potential implications for physical movement, sense of presence, and overall usability. To determine which approach best meets our objectives of improving presence while improving usability, a comparative study was designed to empirically evaluate these two locomotion methods. Chapter 5 presents the detailed methodology for this comparative study, but the implementation of both versions is explained in the next section.

## 4.3 Implementation

The implementation of the eye gaze-based locomotion methods was realized using Unity 6 and the OpenXR framework, which provided standardized access to the eye tracking capabilities of the HTC VIVE Pro Eye headset. In contrast to the free-roaming approach, a target-based system was implemented to provide more controlled navigation within the virtual exhibition space. To support better alignment between physical and virtual environments, navigation targets were placed in strategic locations throughout the IVR space, such as alongside walls, near paintings or near explanatory texts (see Figure 4.1).

**Figure 4.1:** Target placement at strategic locations in the exhibition space, showing how targets were positioned to optimize viewing of artworks while maintaining navigation options.

These target points ensured that the virtual wall that displayed the object of interest, be it a painting or text, was spatially aligned with the real-world boundary of the user. This design decision was based on observations from earlier studies, in which participants using controller-based locomotion sometimes attempted to move closer to an artwork but were blocked by a mismatch between physical and virtual boundaries. By aligning the navigation points with the physical walls, we aimed to reduce such confusion and support a more natural exploration of the exhibition. Although this somewhat restricted free movement within the virtual space, it still provided users with freedom of choice regarding which locations to visit while maintaining greater control over positioning for optimal viewing of the artworks.

### 4.3.1 Eye gazed based portals

The portal-based navigation system was designed to create a more engaging transition between different locations in the virtual exhibition. When a user looked at a painting for approximately 1 second, a visual border filling animation would appear around the painting, providing feedback that the system was registering the user's gaze (Figure 4.2). This dwell time was selected based on previous research that indicated that dwell times for novice users typically range from 450 ms to 1 second [46], suggesting that a 1 second threshold would accommodate users with limited eye-tracking experience while minimizing accidental activations.


**Figure 4.2:** Sequential border filling animation with eye icon indicating gaze direction during dwell time for portal creation.

#### Visual appearance of portals

The visual design of the portals was inspired from established visual representations in popular media such as the video game "Portal" (Valve Corporation, 2007) and films like "Doctor Strange" (Marvel Studios, 2016). (Figure 5.1)

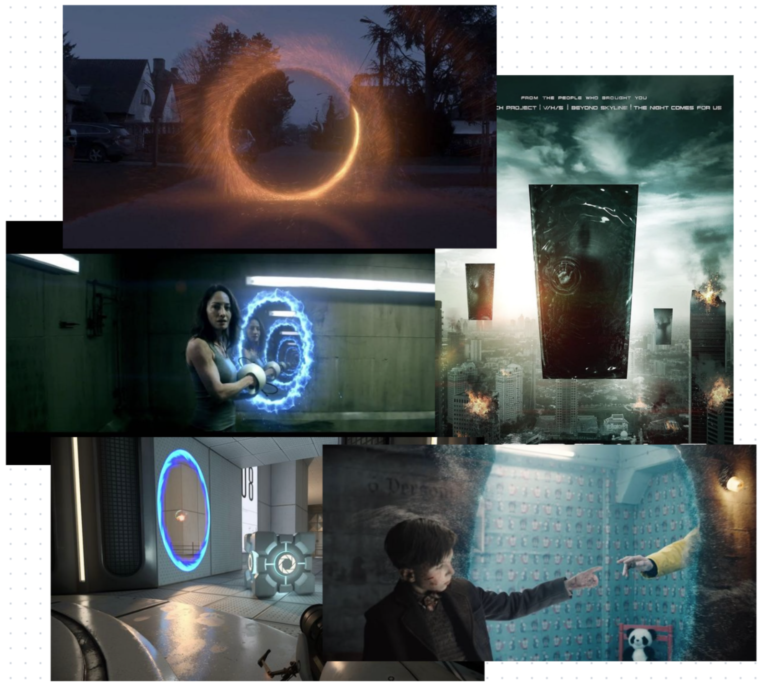

**Figure 4.3:** Portal design inspirations from popular media: Doctor Strange - movie (top), Portals - movie (top right), Portal: No Escape - Short film (middle left),Portal game - Game (bottom left), and Dark - TV Series (bottom right).

The use of familiar metaphors from popular culture in interface design is supported by several researchers in the field. It is argued that using established mental models can reduce cognitive load during interaction with new systems. [47] In the context of virtual environments, borrowing recognizable visual elements from popular media can help users more quickly understand the function and affordances of interactive elements [48]. This approach of borrowing established visual metaphors is particularly relevant when designing for adolescents, who may have significant exposure to these media references, potentially making the interaction more intuitive without extensive instruction or onboarding.

Once the dwell time threshold was reached, a portal would spawn in the center of the play space with an offset of 1 meter from the exact center towards the opposite side based on the player's current position. This offset was implemented to prevent the portal from appearing within the user's personal space, which could be disorienting or uncomfortable, as identified in early testing. The decision to spawn portals in the center of the physical play space was made to address spatial constraints in room-scale VR setups. Placing portals directly in front of users could eventually lead them to the boundaries of the physical space, potentially causing collisions with real walls when attempting to traverse the portal. By maintaining the portal spawn location at the center of the play area, users could be kept within the safe interaction zone while still providing access to different virtual locations. However, preliminary testing revealed that this approach was not optimal for all participants and teleport targets. The implementation proved particularly problematic when multiple teleport locations were oriented in the same direction within the virtual space. In such cases, participants would walk from the center to traverse a portal, only to find themselves positioned at the center again after teleportation, with the next portal also requiring movement back to the same central location.

To guide the user's attention, an animated line was rendered between the target location visible through the portal and the portal on the user's side. (Figure 4.4) This visual element was designed to create a sense of connection between the two locations and help users understand the portal's function intuitively.


**Figure 4.4:** The line creating a sense of connection between the two portals

In addition, blue footstep indicators were projected on the floor leading through the portal (Figure 4.5), subtly suggesting the expected movement.

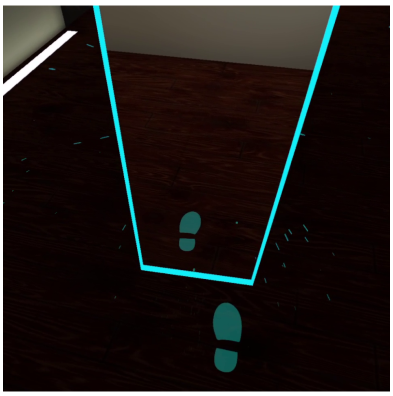

**Figure 4.5:** Blue footstep indicators guiding users toward the portal.

### 4.3.2 Eye gazed based teleportation

The eye gaze teleportation method implemented a more conventional approach to virtual navigation, similar to standard teleportation methods but controlled by eye gaze rather than hand controllers. Users could initiate teleportation by looking at the floor in front of a painting for approximately 1 second, as rated as potentially useful for object selection. [49] This approach is more commonly described in the VR locomotion literature and represents a natural evolution of traditional controller-based teleportation methods. [44], [50], [51] Similar to the portal method, a visual indicator in the form of a blue border appeared at the target location and filled over the 1-second dwell time period (Figure 4.6). Once filled in, the user would be instantly teleported to that location. This immediate transition differs significantly from the portal method, which required physical movement to complete the navigation action.


**Figure 4.6:** Sequential blue box filling animation with eye icon indicating gaze direction during dwell time for teleportation.

This teleportation approach was designed to be functionally similar to the controller-based navigation that had been used in previous studies with the same virtual exhibition, allowing for more direct comparison while removing the need for physical controllers. The primary advantage of this approach is its familiarity with users who have previous experience with VR applications, potentially reducing the learning curve for some participants.

## Chapter 5

# Method

Based on the challenges identified in the preliminary studies and the potential of eye gaze-based interactions, this research focuses on addressing the main research question: "How can eye gaze-based locomotion methods enhance adolescent engagement with immersive virtual cultural heritage exhibitions?"

To systematically approach this complex question, the current study addresses all three sub-questions: "What eye gaze-based locomotion designs are most intuitive and usable for young people in virtual exhibition environments?", "How does eye gaze-based locomotion influence physical movement and presence experience in virtual cultural heritage spaces?", and "To what extent does eye gaze-based locomotion usability affect young people's viewing time behaviors with virtual artworks in IVR?" These questions build on each other to establish a foundational understanding of how interaction design affects user experience before more complex engagement outcomes can be investigated.

A within-subject experiment design was used to investigate how different gaze-based locomotion methods affect presence in immersive virtual cultural heritage exhibitions. The study compares two distinct locomotion techniques: direct eye gaze teleportation and portal-based eye gaze locomotion. The methodology was designed to measure the differences in physical movement, sense of presence, and usability between these interaction paradigms.

By conducting a controlled comparison between these locomotion techniques, the research aims to address the observed challenges with traditional controller-based navigation identified in preliminary studies. Previous observations indicated that adolescents often struggled with controllers, exhibited limited physical movement, and became distracted by navigation mechanics rather than engaging in exhibition content. This methodology provides a framework for systematically evaluating whether eye-gaze based locomotion can mitigate these issues, potentially improving usability and immersion when engaging with the diversity narratives presented in the exhibition content.

## 5.1 Participants

Participants were recruited by convenience sampling, primarily from the university student population. The target age range was 18-28 years, selected to align with the young adult demographic while ensuring that participants could provide independent informed consent while ensuring enough participants would be able to join without financial or credit compensation. This age group also represents an important segment of potential museum visitors who may benefit from improved accessibility to cultural heritage exhibitions.

Special attention was paid to recruiting participants with limited or no previous virtual reality experience. This sampling strategy was deliberate, as previous studies indicated that VR novices often encounter greater difficulties with navigation and may become more distracted by complex interaction mechanics. Using inexperienced users, the study aimed to better evaluate the intuitiveness of gaze-based eye locomotion methods and their potential to improve accessibility for broader audiences.

The study aimed at a minimum of 24 participants. This target was determined to ensure that we had at least 6 participants per condition in the counterbalanced design, which includes four different combinations of locomotion methods and exhibition layouts. The sample size was also informed by similar Human-Computer Interaction (HCI) studies examining locomotion methods in virtual reality environments, where comparable numbers of participants have been used. In addition, the target aligns with the number of participants in preliminary studies conducted with high school students.

## 5.2 Experimental design

A within-subjects (repeated measures) design was implemented in which each participant experienced both locomotion methods and both virtual exhibition layouts. This approach was chosen because of several methodological advantages. Each participant served as their own control, reducing the impact of individual variations in spatial cognition, technology affinity, and physical mobility that could otherwise influence the results when comparing different groups. In addition, participants could provide informed comparisons between the two locomotion methods after experiencing both, allowing more nuanced feedback on the relative strengths and limitations of each approach. This within-subjects design was particularly important given the exploratory nature of eye gaze-based locomotion research, where individual differences in comfort with new interaction paradigms could significantly affect the interpretation of results.

To keep the environment interesting enough to explore for the second time, the original exhibition was split into two layouts. Similar paintings were distributed in these layouts to ensure comparable experiences in both conditions (see Figures 5.1 and 5.2).

### 5.2.1 Counterbalancing

To mitigate potential order effects and and minimize learning effects, counterbalancing was implemented in both locomotion methods and exhibition layouts. This resulted in four possible conditions:

1. Eye teleportation in Layout 1, followed by Portal method in Layout 2 (N = 7)
2. Eye teleportation in Layout 2, followed by Portal method in Layout 1 (N = 8)
3. Portal method in Layout 1, followed by Eye teleportation in Layout 2 (N = 6)
4. Portal method in Layout 2, followed by Eye teleportation in Layout 1 (N = 7)

Participants were assigned condition orders using random assignment, followed by minimal adjustment to ensure counterbalancing throughout the study. This approach aimed to distribute each condition evenly between test positions.

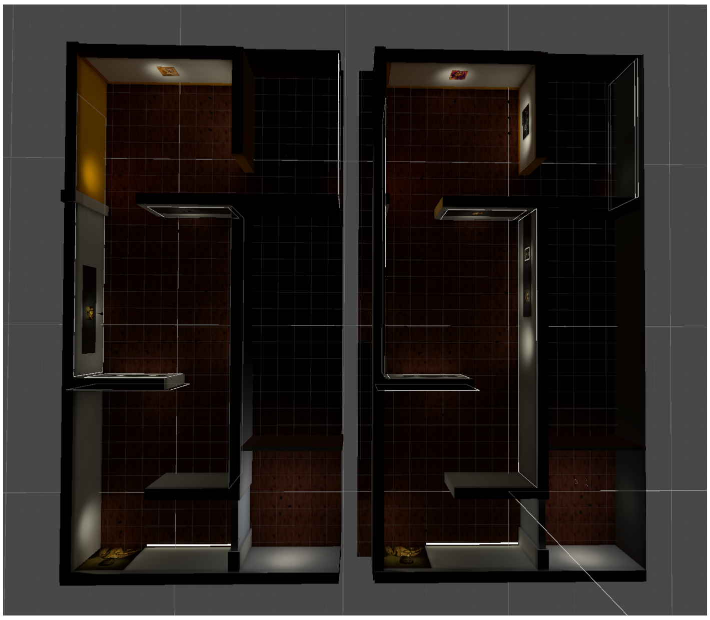

**Figure 5.1:** The two exhibition layouts used in the study. Both layouts maintain the same spatial configuration while displaying different content to ensure comparable experiences across conditions


**(a):** Layout 1


**(b):** Layout 2

**Figure 5.2:** Two versions of the exhibition layout (Layout 1 and Layout 2), designed to control for content familiarity by matching visual elements across corresponding positions (e.g., both layouts show a portrait at the same position), allowing a fairer comparison of user interactions.

### 5.2.2 Independent variables

The primary independent variable in this study was the locomotion method, with two options:

- **Direct eye gaze teleportation**: Participants could teleport to a location by looking at a designated area on the floor in front of a painting and maintaining their gaze for a 1 second dwell time.
- **Portal-based eye gaze locomotion**: Participants generated a portal by fixating their gaze on a painting for 1 second, after which a portal would appear connecting their current position to the area in front of the painting. They would then physically walk through the portal to reach the destination.

To control for content familiarity effects in the within-subjects design, two exhibition layouts (Layout 1 and Layout 2) were created with comparable visual features across corresponding positions (e.g., if position 1 in Layout 1 contained a portrait, position 1 in Layout 2 also contained a portrait).

### 5.2.3 Dependent variables

Four dependent variables were measured to evaluate the locomotion methods. One, physical movement, captured quantitative measures of participant movement within the physical play space, including total distance traveled, area covered, and movement patterns. Two, presence assessed the subjective sense of being present within the virtual environment, measured using the IGroup Presence Questionnaire (IPQ). Three, usability evaluated the perceived ease of use and satisfaction with the locomotion method, assessed using the System Usability Scale (SUS). Four, user preference gathered qualitative feedback on participant preferences between the two locomotion methods through post-experience interviews and comparative assessments.

## 5.3 Materials and apparatus

### 5.3.1 Physical environment

The experiment was conducted in a controlled laboratory setting with a designated physical play space measuring 2.52m × 3.94m. This area was cleared of obstacles and marked with physical boundary indicators to ensure the safety of the participants. The dimensions were chosen to provide sufficient room for physical movement while representing a realistic space limitation that might be encountered in typical usage scenarios.

### 5.3.2 Hardware

The virtual reality experience was delivered using an HTC VIVE Pro Eye head mounted display, which features integrated eye-tracking capabilities essential for the implementation of gaze-based interactions. The base stations of the system were placed to ensure optimal tracking coverage throughout the physical play space. To capture detailed movement data, Unbound XR foot straps with HTC trackers 3.0 [1] were attached to participants' feet. These trackers provided precise spatial positioning of foot movements at a sampling rate of 90 Hz, allowing for a more comprehensive analysis of participants' physical movement patterns during the study. The foot trackers were calibrated before each session to ensure accurate spatial registration in the VR environment. The VR system was connected to a high performance laptop that met the recommended specifications for smooth rendering of the virtual environment.

### 5.3.3 Software

The virtual exhibition and locomotion methods were developed using the Unity game engine, integrated with the Tobii XR SDK[2] through OpenXR[3] for eye tracking functionality. This architectural choice resulted in a hard decoupling from the Tobii

[1] https://www.vive.com/eu/accessory/tracker3/
[2] https://developer.tobii.com/xr-sdk/
[3] https://www.khronos.org/openxr/

drivers, which makes it possible to use other Head-Mounted Display (HMD) devices that have implemented the OpenXR eye tracking layer. Different interactions were implemented in C to handle the eye gaze interactions, teleportation mechanics, portal generation, and data logging of movement and interaction metrics. Within the update to the new Unity 6 game engine, the newest rendering pipeline was implemented (Universal Render Pipeline (URP)), offering improved performance and visual quality compared to the built-in render pipeline used in earlier versions. To render portals within this render pipeline, the open source VRPortalToolkit from the Wearable Computer Lab at University of South Australia was used [52].

## 5.4 Procedure

### 5.4.1 Participant briefing and setup

Upon arrival, participants were briefed about the general purpose of the study without revealing specific hypotheses that could bias their behavior. They were informed that they would experience two different parts of the same virtual exhibition and would be asked to provide feedback after each part. After obtaining informed consent, demographic information and prior VR experience were recorded.

The VR headset was then fitted and adjusted for comfort. The foot trackers with Unbound XR straps were securely attached to the participants' feet and calibrated to ensure accurate tracking. After that, a standard eye tracking calibration procedure was performed using the eye tracking driver to ensure accurate gaze detection. The calibration was confirmed on a screen where participants could look at gray dots that would highlight when looked at. Participants were informed that they would know when the trial was over, but they could also stop at any moment if they felt done or wanted to quit.

### 5.4.2 Getting familiar

For each trail, the participant was placed at a fixed starting point facing the same direction in the physical space, marked by tape on the floor.

Before starting the trial recording, the participants were able to view the first content of the virtual exhibition in the virtual environment where they could familiarize themselves with the first locomotion method they would experience. The instructions were intentionally kept minimal to assess the intuitiveness of each interaction technique. For the eye-based teleportation, participants were simply told: "You can now look at the floor in front of a painting to navigate the virtual exhibition." For the portal method, the instruction was: "You can look at a painting to navigate the virtual exhibition."

To keep the experience as comparable as possible the experience, recording of movement data began when the participant teleported from the first painting (the practice painting) to a second painting within the exhibition. Starting the recording after going to the second painting confirmed that the participants understood and could use the locomotion method before proceeding to the experimental trial.

### 5.4.3 Trials

Once the recording started after the first painting, the participants were given 3 minutes to freely explore the exhibition using the assigned locomotion method. This duration was chosen based on pilot testing to allow sufficient exploration time while preventing fatigue or boredom, especially important in a within-subjects design where participants would experience multiple conditions.

To create a natural exploratory behavior similar to an actual museum visit, participants were explicitly told that there was no specific goal of the experience and that they could explore in their own time according to their interests. The researcher remained in the room, but kept silence unless the participant had questions or encountered difficulties.

### 5.4.4 Questionnaire administration

After completing the first experimental condition, participants were asked to remove the VR headset and complete the IPQ and SUS questionnaires regarding their experience. They were offered a short break before proceeding to the second condition.

The procedure was then repeated with the alternative locomotion method and the exhibition layout according to the counterbalanced assignment. After experiencing both conditions and completing the questionnaires for the second method, the participants provided additional feedback on their preferences and experiences in a brief semi-structured interview.

## 5.5 Data collection methods

### 5.5.1 Quantitative measures

Several quantitative measures were collected to evaluate locomotion methods:

- **VR session data**: During each play session, comprehensive tracking data was recorded at every frame, capturing the following parameters:

  - Timestamp
  - Player position coordinates (x, y, z) in the virtual environment
  - Play space position coordinates (x, y, z) relative to the physical room
  - Object name (name of painting or text that is looked at)
  - Distance to object
  - Gaze position coordinates (x, y, z) in the virtual environment
  - Object gaze coordinates (x, y) on the surface of viewed objects
  - Left foot position coordinates (x, y, z) captured by the foot tracker
  - Right foot position coordinates (x, y, z) captured by the foot tracker
  - Portal A position coordinates (x, y, z) for the entry portal (when applicable)
  - Portal B position coordinates (x, y, z) for the exit portal (when applicable)

- **IGroup Presence Questionnaire (IPQ)**: The IPQ was administered after each condition to measure subscales of the sense of presence of the participants. The following three dimensions of presence (spatial presence, involvement, and presence) were used.

- **System Usability Scale (SUS)**: The SUS provided a standardized measure of perceived usability for each locomotion method. This 10-item questionnaire produces a score between 0 and 100, with higher scores indicating higher perceived usability.

### 5.5.2 Qualitative Measures

In addition to quantitative data, qualitative insights were gathered through two methods. First, observational notes were taken as the researcher documented observable behaviors, difficulties encountered, verbal comments, and apparent engagement levels during the trials. Second, semi-structured interviews were conducted following completion of both conditions, where participants answered questions about their preferences, perceived differences between the locomotion methods, and suggestions for improvement. These responses were audio-recorded and transcribed for analysis.

## 5.6 Data analysis

### 5.6.1 Quantitative data analysis

The movement data required extensive pre-processing before meaningful analysis could be performed. The raw tracking data contained various inconsistencies and noise that needed to be addressed to ensure reliable results. The first step involved time standardization, where all movement data was normalized to a consistent 180-second window. This normalization was essential to allow fair comparisons between participants and experimental conditions, as some sessions experienced minor variations in duration due to technical factors.

Following time standardization, a median filter was applied to position coordinates to compensate for tracking errors that occurred during data collection. This filtering approach was chosen because it could effectively remove unreliable data points without requiring predetermined thresholds that might introduce bias into the analysis. The median filter proved particularly effective in ensuring more consistent movement measurements throughout the analytical process.

The coordinate transformation represented another crucial preprocessing step. Rather than using virtual environment coordinates, the analysis focused on play space coordinates to examine physical movement patterns independently from virtual navigation behaviors. This approach allowed for a clearer understanding of how the different locomotion methods influenced actual physical movement within the experimental space.

Movement per minute was calculated by computing the Euclidean distance between successive position measurements and dividing by the actual time spent exploring. For the portal condition specifically, multiple analyzes were performed with varying post-portal exclusion periods of 0, 1, and 2 seconds, as shown in Figure 5.3. In addition, the data are processed without any exclusion. This approach was necessary to distinguish between the mandatory movement required for portal traversal and any additional exploratory movement that participants might engage in after reaching their destination.

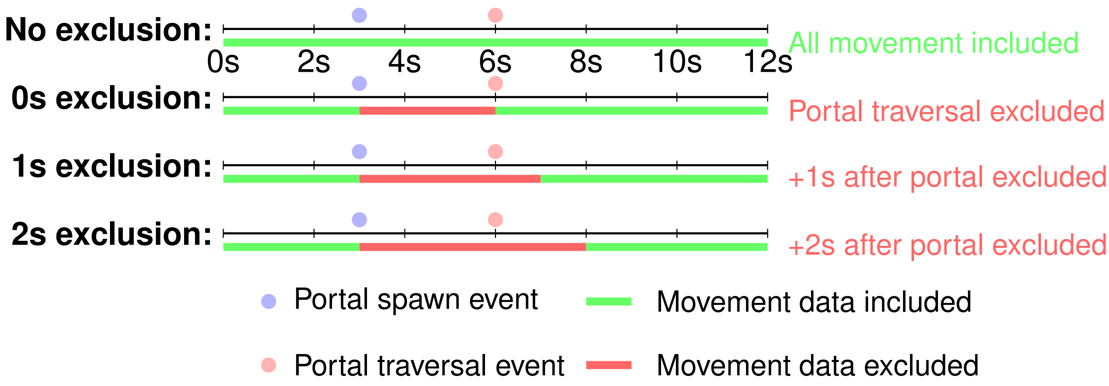


**Figure 5.3:** Timeline examples showing different exclusion periods applied to movement data analysis after portal traversal events. The approach distinguishes between mandatory portal movement and exploratory movement patterns.

Statistical analysis of movement data used a paired sample t-test approach, which enabled comparisons between subjects between the two locomotion methods while controlling for individual differences in movement tendencies. The significance level was established at $p < 0.05$, following standard conventions in HCI research.

### 5.6.2 Themes for qualitative data

The qualitative data analysis was guided by observations from preliminary studies, ensuring continuity in the understanding of key issues. Themes were selected to address the specific challenges identified in controller-based navigation, such as:

- **Ease of use and intuitive interaction**: Addressing navigation challenges observed in preliminary studies, where participants struggled with controllers.
- **Physical movement**: Examining whether the eye gaze methods affected the limited physical movement observed in preliminary studies.
- **Immersion and reduced immersion**: Investigating factors that enhanced or diminished the sense of presence, related to technology distraction observed previously.
- **Usability issues**: Identifying ongoing interaction challenges with eye gaze methods, compared to controller-based challenges observed in preliminary studies.
- **Physical space awareness**: Examining whether participants' concerns about physical space limitations persisted across interaction methods.

Direct quotations were selected to illustrate these themes and provide descriptions of the experiences of the participants. This analysis approach aimed to help to understand how different locomotion methods influenced physical movement, presence, and engagement with the virtual exhibition content.

## 5.7 Ethical considerations

The study was designed with several ethical considerations that were addressed throughout the research process. The research was carried out with the approval of the Ethics Committee for Computer Information Science, which had been obtained for previous studies using the same experimental setup. This existing approval provided the necessary institutional oversight for the current research. All participants provided their informed consent in writing after receiving information about the experimental procedure, data collection methods, and their right to withdraw at any time without consequence. Given the nature of the virtual reality experience, the physical play area was cleared of obstacles and participants were informed about the virtual boundary system designed to prevent collisions with real-world objects. In addition, all data collected were anonymized and stored securely according to data protection regulations. Eye tracking data was processed directly on the device, and no stored images of participants' eyes were retained in the system.

# Chapter 6

# Results

This chapter presents the quantitative and qualitative findings from our comparative study of two eye gaze-based locomotion methods in the context of an IVR cultural heritage exhibition. The analysis focuses on addressing our research questions regarding presence experience, system usability, and user preferences.

## 6.1 Analysis of movement data

To quantify the differences in physical movement between the two locomotion methods, a comparative analysis of the distance traveled per minute by the participants was calculated. The analysis examined both absolute movement rates and paired differences between the portal-based method and eye gaze teleportation under different data exclusion conditions.

### 6.1.1 Data filtering

Several recording sessions experienced technical issues that required special handling during analysis. Eight specific session recordings (participants 3b, 4b, 5a, 5b, 11b, 21b, 25a, and 28a) were flagged for foot tracking errors based on visual inspection of the data. These errors manifested as prolonged periods of missing data or complete signal loss. These tracking failures appeared to be the result of foot trackers being physically blocked during movement or trackers inadvertently shutting off mid session. For comparative analyzes involving foot movement metrics, for these flagged trails, both conditions were excluded from this movement analysis to avoid impact on the comparison. This approach ensured that only sessions with reliable foot tracking data contributed to foot-specific movement analyses, while still allowing these sessions to contribute to other metrics such as gaze data and qualitative feedback, which remained unaffected by foot tracking issues. This unintentionally resulted in a slight imbalance in the remaining sample.

### 6.1.2 Absolute movement analysis

Figure 6.1 shows the total physical movement for both navigation methods under different exclusion conditions. For the portal-based method, participants were required to physically walk through virtual portals, which could potentially inflate movement measurements. To account for this, we implemented various exclusion periods after the mandatory portal traversal movements.

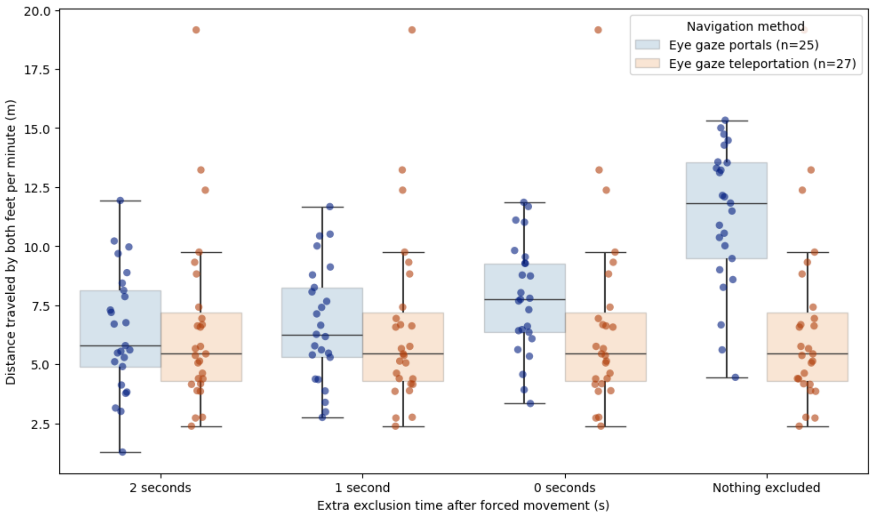


**Figure 6.1:** Difference in physical movement per minute between portal-based and eye gaze teleportation methods. Statistical significance decreases with increasing exclusion periods, suggesting additional movement was primarily associated with portal traversal rather than spontaneous exploration.

As shown in Figure 6.1, the portal-based navigation method generally resulted in higher rates of movement per minute compared to eye gaze teleportation when no data were excluded. However, this difference became less pronounced as longer time windows of post-portal movement data were excluded.

Table 6.1 presents the descriptive statistics for both navigation methods under each exclusion condition. The portal-based method showed higher mean movement rates across all conditions except the 2-second exclusion period, with decreasing magnitude as the exclusion period increased.

**Table 6.1:** Descriptive statistics for total movement distance (meters per minute) by navigation method and exclusion condition.

| Exclusion condition | Condition | N | Mean | SD | Min | Max |
|---|---|---|---|---|---|---|
| | Eye gaze teleportation | 27 | 6.54 | 3.70 | 2.38 | 19.16 |
| 2 seconds | Portal | 25 | 6.40 | 2.59 | 1.28 | 11.94 |
| 1 second | Portal | 25 | 6.70 | 2.48 | 2.75 | 11.67 |
| 0 seconds | Portal | 25 | 7.77 | 2.35 | 3.34 | 11.86 |
| Nothing excluded | Portal | 25 | 11.28 | 2.98 | 4.45 | 15.33 |

### 6.1.3 Paired difference analysis

To control for individual differences in movement tendencies, we also conducted paired t-tests comparing each participant's movement across the two methods. Figure 6.2 displays the differences in the total distance of movement between the methods, with positive values indicating greater movement with the portal-based method.

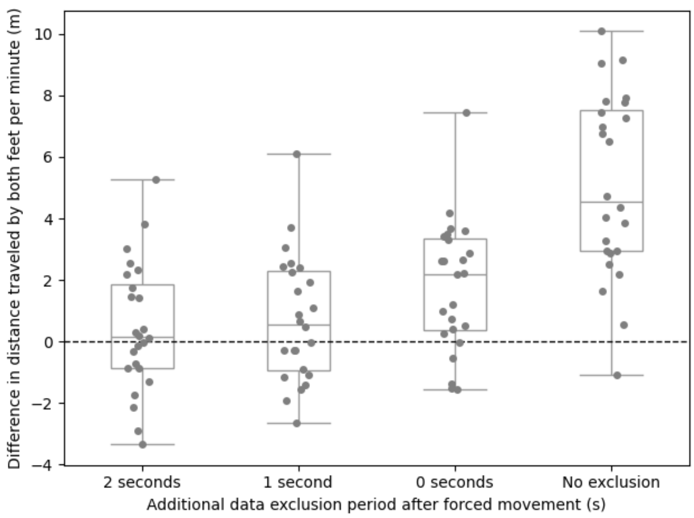


**Figure 6.2:** Difference in physical movement between portal-based and eye gaze teleportation methods. Positive values indicate greater movement with portal method.

The results of the paired t-tests are presented in Table 6.2. The statistical significance of the movement differences varied according to the exclusion period applied.

**Table 6.2:** Results of paired t-tests comparing total movement distance per minute between portal-based and eye gaze teleportation methods under different data exclusion conditions.

| Exclusion Condition | t-statistic | p-value |
|---|---|---|
| Nothing excluded | 8.33 | < .001* |
| 0 seconds after portal | 4.15 | < .001* |
| 1 second after portal | 1.74 | .094 |
| 2 seconds after portal | 1.01 | .321 |

* p-values < .05 are considered statistically significant. The results remain significant even after applying a Bonferroni correction for multiple comparisons ($\alpha = .0125$)

The analysis demonstrates that, with no exclusion period, participants moved significantly more per minute with the portal-based method. This significant difference persisted when excluding only the direct portal traversal movements (0 seconds condition). However, when excluding data for 1 or 2 seconds after portal traversals, the differences became nonsignificant, as shown in Table 6.2. These statistical tests were conducted using two-tailed paired t-tests with 23 degrees of freedom.

## 6.2 Comparison of presence scales

To understand how the different navigation methods influenced the participants' sense of presence in the virtual exhibition, we analyzed dimensions measured by the IGroup Presence Questionnaire (IPQ): spatial presence (Spatial Presence (SP)), involvement (Involvement (INV)) and the sense of being there (G1), where Experienced Realism was not relevant for this comparison. [1] For each participant, the difference in scores between both locomotion methods was calculated after reversing the scores of the inversely formulated items, with positive values indicating higher scores for the portal-based method.

Figure 6.3 illustrates the differences in presence scores between the two navigation methods in all three measured dimensions. The distribution of difference scores provides information on how consistently one method outperformed the other in terms of subjective presence experience.

As shown in Figure 6.3, the most pronounced difference appeared in the spatial presence dimension, where the portal-based method generally received higher

[1] Later we realized that this decision limited the ability to assess overall presence as a complete construct, as noted by Tran et al. [35] regarding the importance of using complete presence measures.

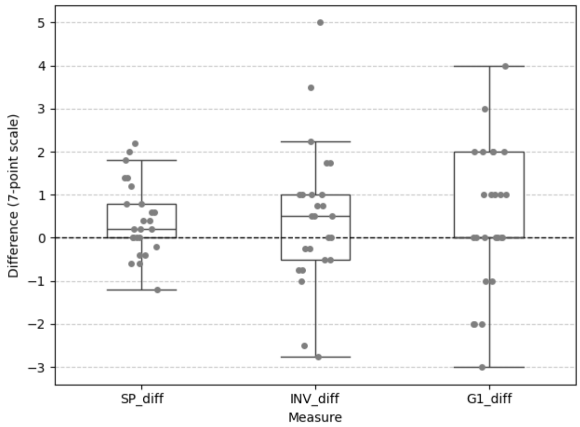


**Figure 6.3:** Differences in presence scores between portal-based and eye gaze teleportation methods across three dimensions: spatial presence (SP), involvement (INV), and sense of being there (G1). Positive values indicate higher scores for the portal-based method.

ratings than the gaze teleportation method of the eyes. The median difference for spatial presence was positive, indicating that most participants reported a stronger sense of 'being there' when using portal-based navigation.

For the involvement dimension, which measures the attention devoted to the virtual environment and the involvement experienced, the differences were less pronounced, but still tended to favor the portal-based method. The wider distribution of scores in this dimension suggests more variability in how participants experienced involvement across the two methods.

Repeated measures MANOVA showed that the main effect of the method on spatial presence and involvement was not statistically significant (F(2, 23) = 3.16, p = .061, Wilks' lambda = .79).

## 6.3 System Usability Scale Scores

To assess the perceived usability of both navigation methods, participants completed the System Usability Scale (SUS) questionnaire after experiencing both locomotion techniques. As shown in Figure 6.4, both navigation methods received generally positive usability ratings. The eye gaze teleportation method achieved a mean SUS score of 76.48 (SD = 10.31), while the portal-based method received a mean score of 73.27 (SD = 15.00). These scores fall within the range typically considered as "good" usability according to established SUS interpretation guidelines. [53]

The difference between the two methods was relatively small, with the eye gaze teleportation method scoring approximately 3.2 points higher on average. A paired

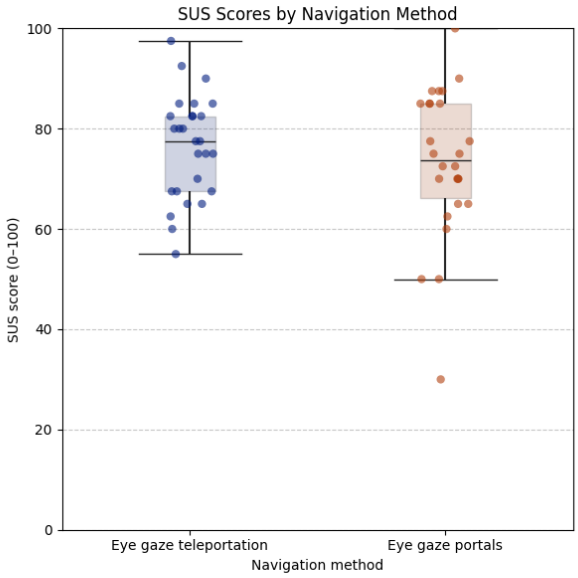


**Figure 6.4:** Distribution of System Usability Scale (SUS) scores for both navigation methods. The eye gaze teleportation method showed slightly higher median usability scores with less variability compared to the portal-based method.

t-test revealed no statistically significant difference between the methods (t(24) = -1.07, p = 0.294). The calculated effect size suggests a small practical difference between the methods, with the eye gaze teleportation method being perceived as slightly more usable.

Both methods demonstrated that gaze-based eye interactions can achieve acceptable usability levels for navigation in virtual exhibitions.

## 6.4 User feedback on navigation methods

This section presents the findings from the qualitative analysis of feedback provided by 29 participants who experienced both navigation methods in the virtual exhibition: eye gaze teleportation and portal-based navigation. The responses are first discussed in relation to eye gaze teleportation and then examined for the portal-based navigation method.

### 6.4.1 Eye-gaze teleportation method

The eye gaze teleportation method enabled participants to navigate the exhibition by focusing their gaze on a desired location to trigger movement. Our qualitative analysis identified several key aspects in relation to the user experience with this method.

**Usability and interaction experience** Many participants described the eye gaze teleportation method as straightforward and accessible. Eight participants explicitly characterized the interaction as "easy" or the Dutch equivalent "makkelijk":

> "It was easy to teleport where I wanted to go." (P2, Trial 2)
>
> "It was easy and intuitive, the eye0tracking worked well!" (P16, Trial 1)
>
> "Het was een stuk makkelijker om te navigeren..." [It was much easier to navigate...] (P26, Trial 2)

Several participants noted that the nature of the interaction felt natural, particularly the ability to look at a destination and move there directly:

> "Looking at the ground to where I wanted to go to felt a lot more natural" (P5, Trial 1)
>
> "Just looking at the place where you want to go" (P17, Trial 2)

Despite the positive reception of the interaction modality, participants reported several specific challenges with the eye gaze teleportation method. Although the designed interaction was intended to respond to looking directly at the ground in front of artworks rather than at the artworks themselves to avoid unintended activations, this implementation led to some confusion and usability issues:

- **Precision and targeting issues:** Nine participants mentioned difficulties with the gaze targeting system not always correctly interpreting their intended destination:

  > "A little confusing because my gaze did not always teleport me where I wanted to go" (P3, Trial 1)
  >
  > "Sometimes you needed to look like right at the ground to teleport and not at the thing you wanted to see" (P27, Trial 1)

- **Inconsistent positioning:** Seven participants noted issues with inconsistent teleportation distances:

  > "The teleport moments were a bit inconsistent in terms of how close I end up at the corresponding painting. Sometimes I had a good distance, but sometimes I “landed“ very very close to the painting" (P11, Trial 1)

- **Unintended movements:** Five participants reported instances of accidental teleportation:

> "there were a few times that I accidentally moved when I didn't mean to" (P20, Trial 1)

> "Ik merkte dat ik tijdens het laden van de vlakken op de grond, alvast wilde kijken naar de kunst. Hierdoor stopte het vlak met laden." [I noticed that while the floor areas were loading, I already wanted to look at the art. This caused the loading to stop.] (P29, Trial 2)

**Impact on experience** Participants reported mixed perspectives on how the eye gaze teleportation method affected their overall experience of the exhibition:

- **Sense of presence:** Eight participants described feeling present or immersed in the museum environment:

> "I felt quite present, like a real museum experience, the quiet room ambience also helped with that." (P7, Trial 1)

> "Ik had het gevoel dat ik echt in het museum stond" [I felt like I was really standing in the museum] (P28, Trial 1)

- **Reduced physical movement:** Seven participants observed that the teleportation method reduced the need for physical movement, with varying opinions on this effect:

> "I didn't have to walk as much as the previous version, which removed some of the immersion in my opinion." (P2, Trial 2)

> "Maybe because I do not need to move a lot so I could concentrate on viewing the painting and reading the explanations." (P10, Trial 2)

- **Movement experience:** Six participants described the teleportation experience itself as potentially disruptive to their sense of presence:

> "I felt a bit like being sucked into the direction i was looking at which was a bit intense." (P15, Trial 2)

> "It felt more passive to navigate through the museum this way" (P15, Trial 2)

### 6.4.2 Portal-based navigation method

The portal method presented participants with doorway-like portals that appeared when gazing at distant locations, which they could then physically walk through to navigate to new areas.

**Immersion and presence** Ten participants specifically mentioned feeling immersed or present in the virtual museum when using the portal method:

> "it felt like being alone in a "real" museum" (P2, Trial 1)

> "I felt quite present in the virtual world." (P7, Trial 2)

> "Bizar hoe je al snel het gevoel hebt dat je in een echt museum bent. De 'echte' wereld om me heen vervaagde helemaal." [Bizarre how quickly you feel like you're in a real museum. The 'real' world around me completely faded away] (P26, Trial 1)

**Physical interaction** Nine participants commented on the physical movement aspect of the portal navigation method, noting how it affected their experience:

> "it was nice to walk around as well." (P5, Trial 1)

> "It was very fun and moving around a bit made me feel more present" (P18, Trial 2)

> "I did not feel compelled to move much, which is usually what makes VR enjoyable and unique in my opinion" (P17, Trial 1)

**Portal orientation challenges** The most frequently reported issue with the portal method related to the positioning of portals in the virtual space. Eleven participants mentioned difficulties with portal placement:

> "One thing that was weird was that most times the portals would spawn just a little behind me, which made navigation a bit weird" (P7, Trial 2)

**Learning process** Eight participants described a process of adaptation to the portal interaction mechanism:

> "Felt quite natural after I learned how the portals worked." (P5, Trial 1)

> "I needed to get used to the stepping through a portal, but after two times I got the hang of it and liked it." (P15, Trial 1)

> "The first one or two doors were not clear but I adapted quickly and then it was almost playful." (P11, Trial 1)

**Unintended Interactions** Seven participants reported issues with portals appearing when they were merely exploring the space visually rather than intending to navigate:

> "Sometimes when looking-observing through the room it would start loading the portal trigger, which was not my intention" (P5, Trial 1)

> "It was also somewhat annoying that if you want to glance at a picture across the room, you start creating a portal for it immediately." (P8, Trial 2)

> "Het enige wat mij af en toe stoorde was het tempo waarmee de portalen verschenen. Soms wilde ik gewoon even rond kijken, zonder meteen naar een nieuwe plek te willen." [The only thing that bothered me occasionally was the pace at which the portals appeared. Sometimes I just wanted to look around without immediately wanting to go to a new place.] (P29, Trial 1)

### 6.4.3 Comparative analysis of navigation methods

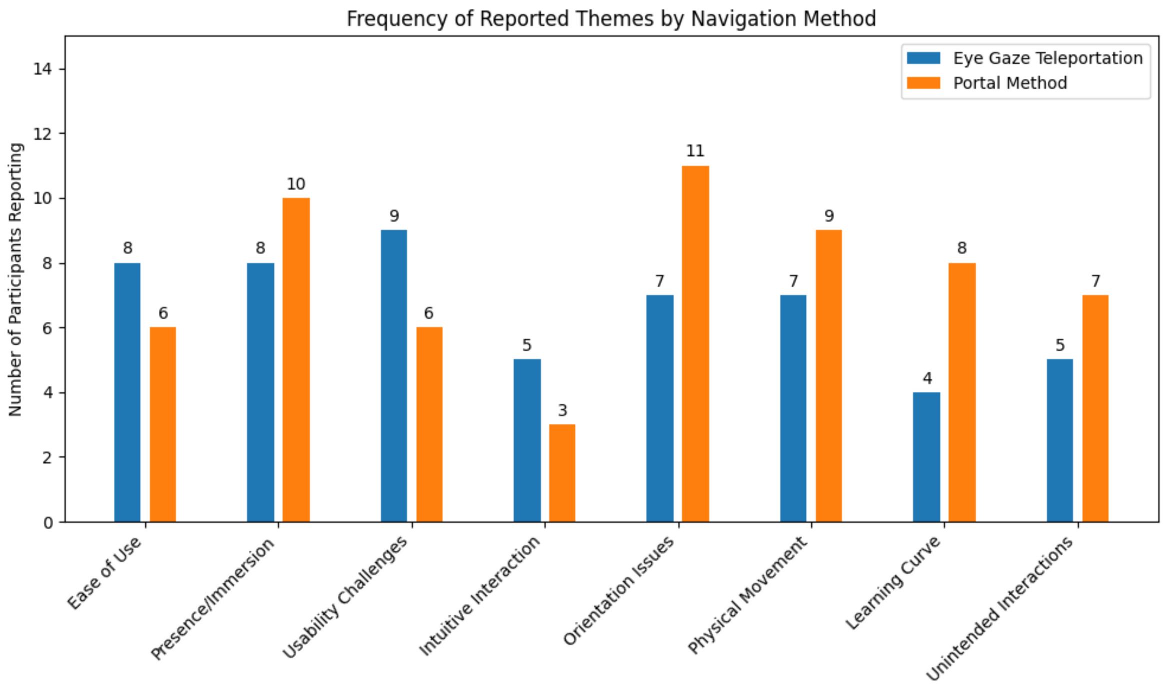


**Figure 6.5:** Enter Caption

Figure 6.5 presents the frequency with which different themes were reported by participants across both navigation methods. The data reveals several notable patterns in participant experiences:

- The eye gaze teleportation method was described more frequently as easy to use and intuitive, with eight participants explicitly mentioning ease of use compared to six for the portal method.
- The portal method was associated with stronger reports of immersion and presence (10 participants) compared to the eye gaze method (8 participants).
- Usability challenges were reported slightly more frequently with the eye gaze method (9 participants) than with the portal method (6 participants).
- Orientation issues were the most commonly reported challenge with the portal method, mentioned by 11 participants, compared to 7 participants reporting similar issues with the eye gaze method.
- The portal method elicited more comments about physical movement (9 participants) and learning process (8 participants) than the eye gaze method (7 and 4 participants, respectively).

Participants who provided feedback on both methods occasionally expressed explicit preferences between them.

> "I find the eyetracking movement to be better than walking through portals." (P4)

> "I did like it [eye gaze], however I prefer the portal one." (P17)

**Physical space awareness** A theme that emerged across both navigation methods was participants' awareness of physical space limitations and concerns about collisions:

> "Only thing that really took me out of the experience was the fact that i was limited by the space of the real room. I couldn't look at some of the paintings naturally, because i was afraid of bumping into a wall." (P7, eye gaze)

> "Still felt quite timid walking around to not bump into real walls." (P7, portal)

> "Het was een beetje raar, omdat ik bang was tegen muren aan te lopen." [It was a bit strange, because I was afraid of walking into walls.] (P28, eye gaze)

## 6.5 Time spent viewing artworks

To understand how the eye gaze-based navigation methods developed in this study compare to more traditional approaches, we analyzed behavioral data from our current participants in addition to data from a previous study that used controller-based navigation in the same virtual exhibition. This comparative analysis focused on the time participants spent looking at paintings during the first three minutes of their experience, which serves as a measure of engagement with the exhibition content.

Figure 6.6 presents a comparison of the total time participants spent looking at paintings through the three navigation methods: eye gaze portals, eye gaze teleportation, and controller teleportation (from preliminary studies).

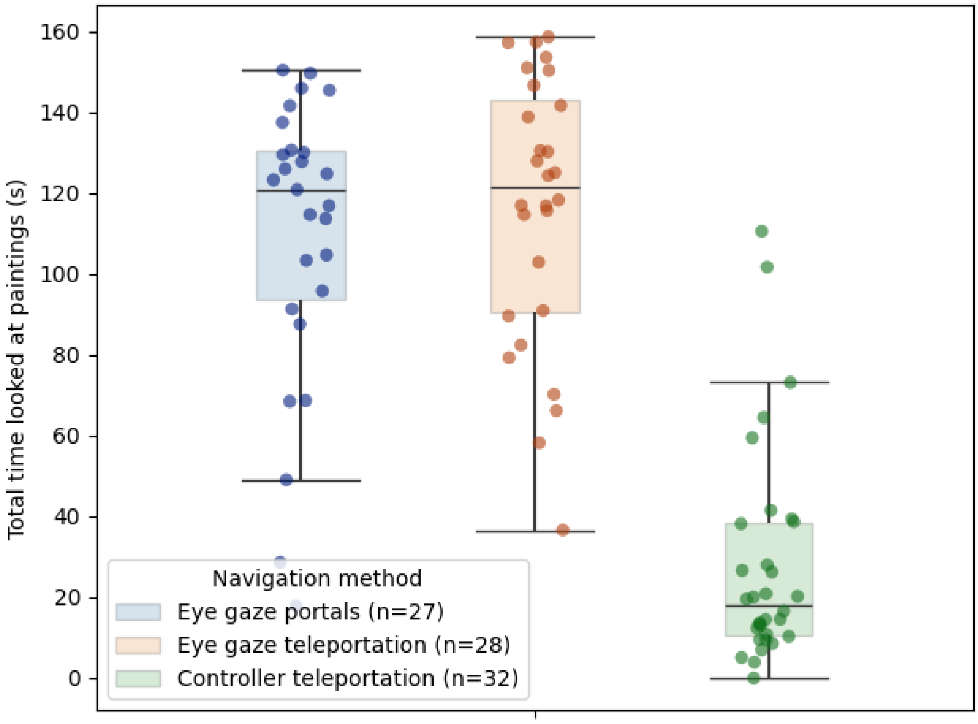


**Figure 6.6:** Comparison of total time spent looking at paintings across three navigation methods during the first three minutes of the virtual exhibition experience.

As shown in Figure 6.6, there was a substantial difference in viewing behavior between the eye gaze-based methods and the controller-based method. Table 6.3 presents the descriptive statistics for each navigation method.

Both eye gaze-based methods resulted in substantially more time spent viewing the artworks compared to the controller-based method. Participants using eye gaze portals spent an average of 108.99 seconds (SD = 35.76) looking at paintings, while those using eye gaze teleportation spent an average of 116.11 seconds (SD = 33.38). In contrast, participants who used controller-based teleportation spent

**Table 6.3:** Descriptive statistics for total time (seconds) spent looking at paintings by navigation method during the first 3 minutes.

| Navigation Method | n | Mean (s) | Std (s) | Min (s) | Median (s) | Max (s) |
|---|---|---|---|---|---|---|
| Eye gaze portals | 27 | 108.99 | 35.76 | 17.75 | 120.81 | 150.39 |
| Eye gaze teleportation | 28 | 116.11 | 33.38 | 36.57 | 121.27 | 158.60 |
| Controller teleportation | 32 | 27.82 | 27.10 | 0.00 | 18.02 | 110.51 |

only 27.82 seconds (SD = 27.10) viewing the artworks during the same time period. While we can observe that the two eye gaze methods yielded similar viewing times, it is important to note that we cannot perform direct statistical comparisons between these methods and the controller-based study due to differences in study conditions, participant groups, and data collection methodologies. However, descriptive statistics reveal interesting differences in viewing behavior between navigation approaches.

# Chapter 7

# Discussion & Limitations

This research aimed to investigate how eye gaze-based interaction methods could enhance adolescents' engagement with cultural heritage in immersive virtual reality exhibitions, with specific focus on the *HERE: Black in Rembrandt's Time* exhibition. By comparing two different locomotion methods, direct eye gaze teleportation and portal-based eye gaze locomotion, the study sought to address the challenges observed in preliminary studies where adolescents struggled with traditional controller-based navigation and became distracted by complex interaction mechanics rather than engaging with exhibition content. The findings reveal interesting insights on the relationship between interaction design, physical movement, presence, and engagement with the content of cultural heritage, while also highlighting the persistent influence of established behavioral patterns in virtual environments.

## 7.1 Discussion of key findings

### 7.1.1 Physical movement and presence

The results indicated that portal-based eye gaze locomotion was associated with significantly more physical movement compared to direct eye gaze teleportation, which is consistent with the findings of Dilanchian et al. [29], who established a positive correlation between user-initiated motion and self-reported presence in IVR environments. However, the relationship between physical movement and engagement may be more nuanced than initially assumed. One participant noted that reduced movement allowed better concentration on "viewing the painting and reading the explanations" (P10, Trial 2), suggesting that excessive movement requirements could potentially distract from content engagement rather than enhance it. This observation indicates that an optimal balance might exist between encouraging physical movement to enhance presence and maintaining sufficient stability to allow focused attention to exhibition content. When examining the data more closely, the difference in movement became nonsignificant after excluding the 'forced' movement required for portal traversal, suggesting that the additional movement was primarily attributable to the locomotion technique itself rather than encouraging spontaneous exploratory behavior. This finding mirrors the mobility challenges observed in the preliminary studies, in which participants using traditional controller-based teleportation demonstrated limited physical movement within the virtual space. Still, the portal method required participants to physically walk through virtual portals, which may have created a stronger connection between the physical and virtual worlds. This physical interaction potentially contributed to the enhanced sense of presence that participants reported. The spatial presence dimension showed slight differences favoring the portal-based method, suggesting that the physical act of walking through portals enhanced the participants' sense of being present within the virtual environment.

### 7.1.2 Usability and user preferences

Both locomotion methods received generally positive usability scores, with direct eye gaze teleportation achieving slightly higher scores on the System Usability Scale (SUS). This difference may be attributed to the relative simplicity of the teleportation method, which allowed participants to reach desired locations with minimal interaction steps. The slightly lower usability scores of the portal method could reflect the additional cognitive load associated with creating and traversing portals. window User preferences were notably divided between the two methods, with many participants describing direct eye gaze teleportation as more efficient for navigation while characterizing the portal-based method as potentially more immersive and enjoyable. This division appears to arise partly from implementation challenges, particularly with respect to portal placement within the play space. Multiple participants reported that portals frequently appeared behind them, requiring awkward backward movement to traverse them. These orientation issues likely influenced user preferences and suggest that refinements to the portal placement algorithm could substantially improve the user experience.

The preference division reflects broader challenges in VR locomotion design identified by Al Zayer et al. [28], who noted that different navigation techniques impact users' sense of presence and spatial understanding in varying ways. The findings suggest that the optimal locomotion method may depend on the participant preferences, the specific objectives of the virtual exhibition, and the intended user experience.

### 7.1.3 Persistent museum behavior patterns

One of the most remarkable observations from both the preliminary studies and the current research was how participants' behavior in the virtual exhibition closely resembled typical behavioral patterns observed in physical museums. Despite being immersed in a virtual environment that afforded different forms of interaction, many participants stood relatively still, maintained conventional viewing distances from artworks, and demonstrated hesitation to interact with elements even when specifically designed to be interactive.

This phenomenon can be understood through schema theory [54], which suggests that individuals rely on existing mental frameworks based on previous experiences to guide their behavior in new but similar situations. Participants likely activated their "museum schema", a mental model of appropriate museum behavior, and transferred these behavioral patterns to the virtual environment. This transfer could explain why, despite the freedom of movement and interaction afforded by IVR, the participants defaulted to conventional museum behaviors such as standing in place and passively observing the artwork.

The persistence of these behavioral patterns across both non-interactive and interactive versions of the exhibition suggests that cognitive schemas are quite robust and resistant to change, even in novel technological contexts. This presents both challenges and opportunities for designing virtual cultural heritage experiences. Although these schemas may limit spontaneous exploration and interaction, they also provide familiar frameworks that could reduce cognitive load and allow users to focus on content rather than learning entirely new behavioral patterns [47].

In the context of eye gaze-based locomotion, these insights are particularly relevant. If users naturally tend toward stationary viewing behaviors in virtual museums, locomotion methods that encourage some degree of physical movement may help counteract these tendencies while still working within familiar conceptual frameworks of museum visitation. This finding suggests that interaction design should carefully balance innovation with familiarity to optimize user experience.

### 7.1.4 Engagement with exhibition content

A particularly promising finding was the increase in the time participants spent viewing artworks when using eye gaze methods compared to data from the preliminary study using controller-based teleportation in the same virtual environment. Participants using eye gaze portals spent approximately 109 seconds, and those using eye gaze teleportation spent around 116 seconds looking at paintings within the first three minutes, compared to only about 28 seconds for controller users.

This difference in viewing time suggests that gaze-based locomotion methods may enhance engagement with exhibition content compared to traditional controller-based approaches. By eliminating manual controller distraction, participants could more naturally focus their attention on the art itself to potentially emotionally engage more, supporting the theoretical framework proposed by Kesner and Horáek [14] regarding the cyclical reinforcement between emotional engagement and aesthetic appreciation during prolonged interaction with art.

Although the comparison involves different groups of participants and study conditions, the substantial magnitude of the difference, approximately four times longer viewing duration, suggests improvements in content engagement. This finding aligns with research by Dondi et al. [19] who suggested that gaze-based interactions can provide more intuitive ways for visitors to engage with exhibitions, allowing them to retrieve information simply by looking at the displayed art rather than struggling with complex interface controls.

The enhanced engagement observed with both eye gaze methods suggests that improved interaction design can facilitate deeper engagement with exhibition content. When users can navigate intuitively and spend more time viewing artworks rather than struggling with interface controls, this may support the educational goals of any cultural heritage exhibition, including those aimed at promoting understanding of underrepresented perspectives in art history. As one participant noted, "Bizarre how quickly you feel like you are in a real museum. The 'real' world around me completely faded away", highlighting the immersive quality that the eye gaze methods achieved, which is crucial for meaningful engagement with the cultural heritage content.

## 7.2 Redesigns for future use

Based on the findings and user feedback, several design improvements have been identified for future implementations of gaze-based eye navigation in VR exhibitions of VR cultural heritage. For the portal-based method, the portal placement algorithm requires refinement to address the frequent issue of portals spawning behind users, which caused awkward navigation experiences. A more sophisticated positioning system could calculate the optimal placement of the portal based on the orientation of the user and the available physical space, ensuring that the portals appear in easily accessible locations.

For the eye gaze teleportation method visual markers were added on the floor to provide clear visual cues indicating where users should look to initiate teleportation. During the original implementation, participants were simply instructed to "look at the floor in front of a painting," which created ambiguity about the exact target location and led to confusion and failed teleportation attempts. The new design includes distinct floor markers that clearly indicate the available teleportation destinations, making the interaction more intuitive and reducing the trial-and-error process that some participants experienced.

Additionally, the virtual exhibition layout has been restored to include all paintings from the virtual *HERE: Black in Rembrandt's Time* exhibition. This expansion addresses the limitation of having two separate subsets of artworks available during the within-subject study.

## 7.3 Implications and recommendations

The findings of this research suggest several important considerations for designing gaze-based interactions in cultural heritage IVR applications. First, the choice of locomotion method should align with the exhibition's primary objectives. Exhibitions prioritizing efficient content delivery and accessibility might benefit from direct eye gaze teleportation, while those emphasizing immersive experiences and physical engagement might consider portal-based approaches, particularly with improved placement algorithms.

The implementation of gaze-based interaction interactions was designed with the Midas touch problem in mind [20], using techniques such as dwell times and visual feedback to reduce unwanted selections. However, the results showed that some participants still experienced occasional false selection, suggesting that this issue is not yet fully resolved in this design. This highlights the need for more research on more robust or adaptive solutions. However, the findings suggest that the eye-gaze interactions have potential as an interaction modality in IVR applications, especially for users who may struggle with traditional controller-based interfaces as observed or in contexts where handheld controllers present logistical challenges. This is particularly relevant in setups with ceiling-mounted HMD suspensions, which are commonly used in commercial systems. In such cases, avoiding wires on the controllers is often preferred.

The observed relationship between interaction design and content engagement highlights the importance of considering locomotion methods as integral components of the exhibition experience rather than merely technical necessities. Design decisions regarding movement and navigation can directly influence how users engage with cultural heritage content, suggesting that interaction designers should work closely with content curators to optimize both technical and educational outcomes.

Furthermore, the persistent influence of museum schemas suggests that VR exhibition designers should carefully consider how to leverage familiar behavioral patterns while strategically introducing novel interaction possibilities. This balance could help reduce cognitive load while still taking advantage of the unique advantages of virtual environments.

Future research protocols should also address technical challenges more explicitly, particularly with regard to the reliability of the tracking system. Several sessions in the current study required exclusion due to foot tracking issues, including standby mode activation and blocking by trousers. These issues could be mitigated through more comprehensive pilot testing with a diverse group of participants, including people who wear different types of clothing that could affect tracking performance, and by implementing more robust system monitoring procedures.

## 7.4 Limitations

Despite the insights gained, several limitations should be acknowledged when interpreting these findings. From a methodological perspective, the participant sample consisted primarily of university students, which could not fully represent the adolescent population targeted in the broader research. This demographic difference could limit the generalizability of the findings to younger adolescents, who may interact with eye gaze-based systems differently due to developmental and experiential factors. In addition, participants experienced each locomotion method for only 3 minutes, which could not capture the adaptation patterns that could emerge with extended use. The brief duration of exposure means that novelty effects could have influenced responses, particularly for participants with limited prior VR experience who might initially focus more on technology itself rather than the exhibition content.

The study's approach to measuring presence also presents certain limitations. While the IGroup Presence Questionnaire (IPQ) treats presence as a multifactor phenomenon consisting of four components (spatial presence, involvement, experienced realism, and general presence), only three dimensions were asked in this research. The decision to exclude the experienced realism component was based on the focus of the research questions, but this selective use of the questionnaire means that what was measured represents only parts of the overall presence experience rather than presence as a complete construct. As noted in previous research, the extraction of only subsets of presence questionnaires limits the ability to draw direct conclusions about the general presence [35]. Future research should consider implementing the complete IPQ to provide a more complete understanding of how different locomotion methods influence the full spectrum of presence experience.

The controlled laboratory environment with a predefined play area also differs quite much from the various physical environments where IVR exhibitions might be implemented in real-world settings. Museums, schools, and other cultural institutions often have different spatial constraints and ambient conditions that could influence user behavior and system performance. Furthermore, eye tracking technology, while advanced, had limitations in terms of precision and reliability that became apparent during the study. Some participants experienced occasional mis-registration of gaze points, which might have affected their user experience and potentially influenced their perceptions of the system's usability.

From a content perspective, the virtual exhibition layouts contained a limited selection of artworks from the original exhibition due to technical constraints. This reduction in content complexity might not fully capture the narrative depth and thematic richness of the complete *HERE: Black in Rembrandt's Time* exhibition, potentially limiting the ecological validity of the findings when considering how these interaction methods might perform in the complete experience.

## 7.5 Future research directions

The findings of this study suggest several promising directions for future research that could build on these initial insights. Research conducted specifically with high school students would provide a valuable understanding of how the target demographic responds to eye gaze-based interactions in cultural heritage contexts, potentially revealing different usage patterns and preferences compared to university students.

Studies designed to directly assess how different locomotion techniques influence appreciation and understanding of diversity themes would address a key limitation of current research. Such studies could examine whether the enhanced engagement observed with eye gaze methods translates to a deeper understanding of the historical and cultural narratives presented in exhibitions focused on underrepresented perspectives.

Hybrid approaches that integrate eye gaze with other interaction modalities could offer complementary benefits for cultural heritage exhibitions. For example, combining eye gaze navigation with gesture-based interactions for specific artwork elements could provide both efficient locomotion and rich content interaction possibilities.

Longitudinal studies investigating user adaptation to gaze-based eye locomotion methods over extended periods could provide information on whether observed patterns persist with increased familiarity and whether user preferences evolve over time. Such research could also examine the durability of any enhanced engagement effects and their potential impact on learning and attitude change.

In conclusion, this research provides initial evidence that eye gaze-based locomotion methods could offer advantages over traditional controller-based navigation in virtual cultural heritage exhibitions, particularly in terms of content engagement and presence. The findings suggest that different locomotion approaches offer various benefits depending on exhibition goals, while highlighting the importance of considering users' natural behavioral tendencies when designing virtual museum experiences. By addressing the identified limitations and building on these initial findings, future research could provide a more comprehensive understanding of how interaction design in IVR might support appreciation of diverse cultural narratives while accounting for users' established behavioral patterns.

## Chapter 8

# Conclusion

This research investigated how eye gaze-based locomotion methods could enhance adolescents' engagement with cultural heritage in immersive virtual reality, focusing on HERE: Black in Rembrandt's Time exhibition. Two navigation techniques were compared: direct eye gaze teleportation and portal-based locomotion. Both methods offered viable alternatives to traditional controller-based navigation. Direct teleportation proved slightly more usable and straightforward, reducing the learning curve associated with controller-based interactions. The portal-based method generated higher spatial presence scores, with participants feeling more immersed probably due to the additional physical movement required. Notably, participants using either eye gaze method spent substantially more time viewing artworks, approximately 109-116 seconds within the first three minutes compared to only 28 seconds for controller users. Although a big difference in the participants and the place might explain this difference, it could also suggest that eye gaze-based interaction significantly improves engagement with exhibition content by reducing manual controller distractions. Participants also transferred conventional museum behaviors to the virtual environment, maintaining traditional viewing distances and familiar behavioral patterns even in the novel technological context. Although neither locomotion method emerged as universally superior, the optimal choice depends on specific exhibition goals: direct teleportation for accessibility and efficient content delivery, portal-based for immersion and experiential aspects. This research demonstrates that thoughtful interaction design can influence user engagement with virtual exhibition content, providing practical guidance for cultural institutions looking for more accessible and engaging VR experiences for younger audiences.

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# Appendix A

# Generative AI usage

During the preparation of this work, ChatGPT [1] and Claude [2] was used in order to assist with writing and structure refinement. After using this tool, the content was thoroughly reviewed and edited as needed, and full responsibility is taken for the final content of the work.

[1] https://chatgpt.com/
[2] https://claude.ai/

# Appendix B

# Thematic Analysis of Navigation Methods

### B.0.1 Coding Framework

The following color-coded framework was used in analyzing participant feedback for both navigation methods:

| **Code** | **Description** |
|---|---|
| EASE OF USE | Comments indicating the navigation method was easy, simple, or straightforward to use |
| INTUITIVE INTERACTION | References to the interaction feeling natural or intuitive |
| USABILITY ISSUES | Difficulties or challenges encountered while using the navigation method |
| VISUAL DESIGN | Comments about the visual elements of the interface |
| IMMERSION | References to feeling present, immersed, or "really there" in the virtual environment |
| REDUCED IMMERSION | Indications that something diminished the sense of presence |
| PHYSICAL SPACE | Comments about limitations due to real-world space constraints |
| MOVEMENT | Descriptions of how movement felt within the virtual environment |
| DESIGN FEATURES | Comments about specific design elements or appreciation |
| ORIENTATION ISSUES | Problems with positioning or orientation of interface elements |

**Table B.1:** Coding framework for thematic analysis

### B.0.2 Eye Gaze Teleportation Method

| Participant Feedback | Code |
|---|---|
| **Participant 2 (Trial 2):** It was easy to teleport where i wanted to go. | EASE OF USE |
| The white boxes were quite bright, and I think only having the blue hazy boxes would be enough. | VISUAL DESIGN |
| I didn't have to walk as much as the previous version, which removed some of the immersion in my opinion. | REDUCED IMMERSION |
| But not having the blue rectangles appear every time I look at a painting was also nice. | |
| **Participant 3 (Trial 1):** A little confusing because my gaze did not always teleport me where I wanted to go, it seemed I also had to use my feet but not entirely sure. | USABILITY ISSUES |
| It was also a little disorienting where in front of the painting I ended up, as sometimes it was very close to where I had to step back or too far to the side. | ORIENTATION ISSUES |
| **Participant 4 (Trial 1):** It was quite easy for me. The eye tracking makes it very easy to move around. | EASE OF USE |
| **Participant 5 (Trial 1):** It was nice, i didnt have to worry so much of looking around the room to other pictures and them loading my portal. | |
| looking at th eground to where i waned to go to felt a lot more natural and less pressure to keep myself from looking to other spots in the room | INTUITIVE INTERACTION |
| **Participant 6 (Trial 2):** This system was easier to use | EASE OF USE |
| than the previous one, though it was a little bit less fun to use. | REDUCED IMMERSION |
| The text was very clear, and the images were sometimes hazy, but that was easily fixed by changing the perspective or stepping closer to the painting. | |
| **Participant 7 (Trial 1):** I felt quite present, like a real museum experience, the quiet room ambience also helped with that. | IMMERSION |
| Only thing that really took me out of the experience was the fact that i was limited by the space of the real room. I couldnt look at some of the paintings naturally, because i was afraid of bumping into a wall. | PHYSICAL SPACE |
| **Participant 8 (Trial 1):** It was easy to enter, | EASE OF USE |

| Participant Feedback | Code |
|---|---|
| although sometimes the Focus for moving around was a bit cumbersome, and I had to try multiple times to get where I wanted to go. | USABILITY ISSUES |
| **Participant 10 (Trial 2):** I think the interaction was easier than the first one. Maybe because I do not need to move a lot so I could concentrate on viewing the painting and reading the explanations. | EASE OF USE |
| **Participant 11 (Trial 1):** I was a little bit confused at the beginning since I did not now how to navigate.<br>The teleport moments were a bit inconsistent in terms of how close I end up at the corresponding painting. Sometimes I had a good distance, but sometimes I “landed“ very very close to the painting, a bit too close for comfort or at least not as how close as I would go.<br>Otherwise it was cool to be able to look around to get an idea about where in the exhibition you are. | USABILITY ISSUES<br>ORIENTATION ISSUES |
| **Participant 12 (Trial 2):** I much prefered this style of navigating, it gave a nicer insight in how it feels, more like the separate "walking-points" were like their own rooms to walk around in. | DESIGN FEATURES |
| **Participant 14 (Trial 1):** It was mainly a bit empty.<br>It wasnt bad but because of the headset I was still a bit afraid to hit a physical wall. It would have been nice to have some outline on the ground or something that could help me know where I can and cant walk.<br>Some audio or narration might also help immerse me more | PHYSICAL SPACE |
| **Participant 15 (Trial 2):** I felt a bit like being sucked into the direction i was looking at which was a bit intense. It was no longer me walking or stepping into a direction, but rather getting sucked into it, which i didnt like so much. I felt like it went really quickly (not a lot of time between first glance and moving there) which also made me lose my orientation at the start.<br>It felt more passive to navigate through the museum this way | MOVEMENT |
| **Participant 16 (Trial 1):** It was easy and intuitive, the eyetracking worked well! | EASE OF USE |
| **Participant 17 (Trial 2):** It was nicer than before,<br>just looking at the place where you want to go to instead of having to backtrack through a portal that would sometimes appear behind you! | INTUITIVE INTERACTION |

| Participant Feedback | Code |
|---|---|
| **Participant 18 (Trial 1):** A little difficult to navigate at first, but it got easier quickly | USABILITY ISSUES |
| **Participant 19 (Trial 2):** I did like it, however I prefer the portal one. By doing that I still had to walk around, whereas with using the ground I could just teleport to the places I had to go. | |
| This kind of removed my feeling of being present in the museum. | REDUCED IMMERSION |
| **Participant 20 (Trial 1):** the navigation itself was okay. | |
| there were a few times that I accidentally moved when I didn't mean to, but that was generally easy to avoid when I knew to look away if the floor started being teal and I didn't want to move. | USABILITY ISSUES |
| I did find that to get a better look at the painting and the text I still needed to walk around a bit in the real world as the intervals between spots I could move were quite large | |
| **Participant 21 (Trial 1):** I really liked the experience and i had the feeling i was really there. | IMMERSION |
| **Participant 22 (Trial 1):** Makkelijk, | EASE OF USE |
| *[Translation: Easy,]* | |
| al was het wel soms zoeken en in het begin onnatuurlijk om je te verplaatsen door te kijken en je hoofd naar beneden te doen. | USABILITY ISSUES |
| *[Translation: though it was sometimes difficult to find and initially unnatural to move by looking and tilting your head downward.]* | |
| **Participant 23 (Trial 2):** It took some time and tries to move from point A to B | USABILITY ISSUES |
| **Participant 24 (Trial 2):** ik vond het heen en weer teleporten niet bijdragen aan de ervaring, het voelde voor mij daardoor nepper en het voelde meer als plaatjes kijken ipv dat ik echt door de ruimte liep. | REDUCED IMMERSION |
| *[Translation: I felt that teleporting back and forth did not contribute to the experience, it made it feel more fake to me and it felt more like looking at pictures instead of actually walking through the space.]* | |
| **Participant 25 (Trial 1):** Ik vond het lijken op een echt museum. Ik kon ook mijn gezicht dichterbij het schilderij houden, wat ik ook in een echt museum zou doen. Ik werd ook nauwelijks afgeleid door mijn omgeving. | IMMERSION |

| Participant Feedback | Code |
|---|---|
| *[Translation: I thought it resembled a real museum. I could also hold my face closer to the painting, which I would also do in a real museum. I was also hardly distracted by my surroundings.]* | |
| Het enige nadeel was dat je niet zelf de hele gang door kon lopen, | MOVEMENT |
| *[Translation: The only disadvantage was that you couldn't walk through the entire corridor yourself,]* | |
| maar het systeem, dat je moet kijken naar de grond, was erg makkelijk te opereren. | EASE OF USE |
| *[Translation: but the system, where you have to look at the ground, was very easy to operate.]* | |
| **Participant 26 (Trial 2):** Het was een stuk makkelijker om te navigeren, | EASE OF USE |
| *[Translation: It was much easier to navigate,]* | |
| maar het zorgde ook voor een hele andere ervaring. Ik had veel minder het gevoel alsof ik echt in een museum was en was me bewuster van mijn omgeving. Het werd inderdaad opeens meer informatieve tekst en plaatjes kijken. | REDUCED IMMERSION |
| *[Translation: but it also created a completely different experience. I felt much less like I was actually in a museum and was more aware of my surroundings. It suddenly became more about looking at informative text and pictures.]* | |
| **Participant 27 (Trial 1):** it was good i liked it | EASE OF USE |
| but sometimes you needed to look like right at the ground to teleport and not at the thing you wanted to see | VISUAL DESIGN |
| **Participant 29 (Trial 2):** Het was in het begin lastig. Ik merkte dat ik tijdens het laden van de vlakken op de grond, alvast wilde kijken naar de kunst. Hierdoor stopte het vlak met laden. Dit gebeurde een aantal keer, voordat ik er elke keer van tevoren al bewust op ging letten als ik naar een andere plek toe wilde. | USABILITY ISSUES |
| *[Translation: It was difficult at the beginning. I noticed that while the surfaces on the ground were loading, I already wanted to look at the art. This caused the surface to stop loading. This happened several times, before I consciously started paying attention to it each time when I wanted to go to another location.]* | |
| Soms wist ik niet helemaal zeker waar het allemaal "mogelijk" was om heen te kijken. | |
| *[Translation: Sometimes I wasn't completely sure where it was all "possible" to look.]* | |

| Participant Feedback | Code |
|---|---|
| **Participant 30 (Trial 1):** Het was een beetje raar, omdat ik bang was tegen muren aan te lopen. | PHYSICAL SPACE |
| *[Translation: It was a bit strange, because I was afraid of walking into walls.]* | |
| Maar voor de rest vond ik de bediening wel heel makkelijk. | EASE OF USE |
| *[Translation: But other than that, I found the controls very easy.]* | |
| **Participant 31 (Trial 1):** Soms pakte hij hem niet heel snel, | USABILITY ISSUES |
| *[Translation: Sometimes it didn't respond very quickly,]* | |
| maar verder was lopen wel makkelijk | EASE OF USE |
| *[Translation: but otherwise walking was easy]* | |

### B.0.3 Portal Method

| Participant Feedback | Code |
|---|---|
| **Participant 2 (Trial 1):** it felt like being alone in a "real" museum, | IMMERSION |
| instead of needing to walk everywhere I could just look at where I wanted to go and the portals, made a smooth transition from painting to painting. | DESIGN FEATURES |
| I prefer this over a joystick to move somewhere as I still need to actually walk to move where I want to go | DESIGN FEATURES |
| **Participant 3 (Trial 2):** I preferred this experience of the exhibition to get to the paintings. | |
| It felt more intuitive and like I ended up at an appropriate distance from the paintings. | INTUITIVE INTERACTION |
| **Participant 4 (Trial 2):** It was quite easy for me. The eye tracking makes it very easy to move around. | EASE OF USE |
| I found it hard to find the exact doorway everytime I wanted to move. | USABILITY ISSUES |
| **Participant 6 (Trial 1):** I enjoyed it a lot. | |
| The mechanics were easy to understand (looking at the picture - waiting for the blue borders to appear - walking through it), and it was easy to read. | EASE OF USE |
| The paintings were a little bit hazy at times, but this could be helped by stepping closer or changing the angle. | |
| **Participant 7 (Trial 2):** I felt quite present in the virtual world. The navigation felt a lot more game-like which contributed to the immersion. | IMMERSION |
| Still felt quite timid walking around to not bump into real walls. | PHYSICAL SPACE |
| One thing that was weird was that most times the portals would spawn just a little behind me, which made navigation a bit weird, and for less technically adept people could be an issue. | ORIENTATION ISSUES |
| **Participant 8 (Trial 2):** It was kind of weird to step back to get in front of the portal to the next paintings. | ORIENTATION ISSUES |
| It was also somewhat annoying that if you want to glance at a picture across the room, you start creating a portal for it immediately. | USABILITY ISSUES |
| **Participant 10 (Trial 1):** The exhibition is graphically presented in the view, which is interactive for me when I was walking around and turning head to different directions. However, I would consider having audio sounds may be more immersive | |

| Participant Feedback | Code |
|---|---|
| **Participant 11 (Trial 1):** Navigating was a bit confusing (More than the other version) since I did not know what those 'doors' were. Since they were small I looked into it from a bit a far and had to walk around to understand that I can actually walk through them. | USABILITY ISSUES |
| So the first one or two doors were not clear but I adapted quickly and then it was almost playful. | INTUITIVE INTERACTION |
| The only thing I noticed, was I sometimes had to take a few steps back and had to walk around the door to be bale to enter. | ORIENTATION ISSUES |
| Not really a bad thing, just took a moment to understand that I have to walk and look around more. | |
| **Participant 12 (Trial 1):** The style of navigating the exhibition through the portals felt a bit strange. | USABILITY ISSUES |
| **Participant 14 (Trial 2):** It was similar to the previous expiriment, in my opinion. With same feedback, I think. | |
| **Participant 15 (Trial 1):** i liked that i could just walk around a bit and come closer to a painting. | MOVEMENT |
| I needed to get used to the stepping through a portal, but after two times i got the hang of it and liked it. | INTUITIVE INTERACTION |
| Was a bit confusing at times when the portal was behind me, but after figuring that out that was no problem. | ORIENTATION ISSUES |
| I liked to project my eyes to where i was going, that felt easy | EASE OF USE |
| **Participant 16 (Trial 2):** It went well, | |
| moving between the portals allowed for a tangible feeling of movement. | MOVEMENT |
| The only thing I was struggling with is the wire of the headset, that kept wrapping around my neck as I turned in one direction intuitively. | MOVEMENT |
| **Participant 17 (Trial 1):** Somewhat weird at first to not move through it but jump through portals. | USABILITY ISSUES |
| I did not feel compelled to move much, which is usually what makes VR enjoyable and unique in my opinion | MOVEMENT |
| **Participant 18 (Trial 2):** It was very fun and moving around a bit made me feel more present, | IMMERSION |
| but I somehow ended up positioned at the wrong side of the portal, making it harder to navigate and step through it. | ORIENTATION ISSUES |
| **Participant 19 (Trial 1):** At first I was a bit confused as how to navigate through the space. | USABILITY ISSUES |

| **Participant Feedback** | **Code** |
|---|---|
| However, after my first interaction it became clear quite quickly. | INTUITIVE INTERACTION |
| The portals were a nice touch, and worked really well. | DESIGN FEATURES |
| **Participant 20 (Trial 2):** It felt more intentional to have to walk through a portal to get to the new spot, | DESIGN FEATURES |
| but it required more active engagement and sort of broke the suspension that I was walking around a normal museum. | REDUCED IMMERSION |
| The portal did look cool though. | DESIGN FEATURES |
| Two things I had some trouble with were that the portal almost always spawned behind me, meaning I had to walk around to go through it and it took more effort than if it spawned in front of me. There was also some paintings that I was close enough to and didn't feel the need to teleport or move again to read, but because every painting is a trigger, it was inconvenient to try to read the text and look at the painting without triggering the portal if I didn't want to. | ORIENTATION ISSUES |
| **Participant 21 (Trial 2):** I really liked the experience of being in the museum. | IMMERSION |
| **Participant 22 (Trial 2):** Deze manier maakte dat ik snel naar de schilderijen kon verplaatsen die ik wilde zien, maar dat ik mij ook goed moest focussen op welke schilderijen ik wilde zien. *[Translation: This method allowed me to quickly move to the paintings I wanted to see, but also required me to focus well on which paintings I wanted to see.]* | DESIGN FEATURES |
| Dat er meerdere portals open konden maakte het een beetje overwhelming *[Translation: The fact that multiple portals could be open made it a bit overwhelming]* | USABILITY ISSUES |
| **Participant 23 (Trial 1):** Relatively easy to use, | EASE OF USE |
| but a bit awkward to walk backwards to go to the next painting | ORIENTATION ISSUES |
| **Participant 24 (Trial 1):** het was een leuke manier van het ontdekken van het museum ten op zichte van bijvoorbeeld een boek *[Translation: it was a nice way of discovering the museum compared to, for example, a book]* | DESIGN FEATURES |
| **Participant 25 (Trial 2):** Ik vond het idee van een portaal een slim idee, *[Translation: I thought the idea of a portal was a clever idea,]* | DESIGN FEATURES |

| Participant Feedback | Code |
|---|---|
| alleen moeilijk te gebruiken. Soms, wanneer je net uit een portal was gestapt, was je zo dicht bij een muur dat je gedesorienteerd was waar je in de ruimte was. *[Translation: just difficult to use. Sometimes, when you had just stepped out of a portal, you were so close to a wall that you were disoriented about where you were in the space.]* Ik merkte dat ik liever op 1 plek stond, dan meerdere schilderijen te bekijken, omdat ik uit mijn concentratie raakte wanneer ik moest zoeken naar de portals. Verder alsnog heel informatieve kunst en voor het verhaal en de expositie zou ik het zeker nog een keer doen. *[Translation: I noticed that I preferred to stand in one place to view multiple paintings, because I lost my concentration when I had to search for the portals. Otherwise, still very informative art and for the story and the exhibition I would definitely do it again.]* | USABILITY ISSUES |
| **Participant 26 (Trial 1):** Ik vond het een hele leuke ervaring. Bizar hoe je al snel het gevoel hebt dat je in een echt museum bent. De 'echte' wereld om me heen vervaagde helemaal. *[Translation: I found it a very nice experience. Bizarre how quickly you feel like you're in a real museum. The 'real' world around me completely faded away.]* Fijn dat je de schilderijen ook van dichtbij kunt bekijken. Alsof je alleen bent en even met niemand rekening hoeft te houden. Je kunt echt de tijd nemen. Super tof! *[Translation: Nice that you can also look at the paintings up close. As if you're alone and don't have to take anyone into account for a moment. You can really take your time. Super cool!]* | IMMERSION |
| **Participant 27 (Trial 2):** i veld really there | IMMERSION |
| and it was a nice that you could look at the pictures and then you could go there instead of looking at the floor. | DESIGN FEATURES |
| **Participant 28 (Trial 1):** Ik had het gevoel dat ik echt in het museum stond, *[Translation: I felt like I was really standing in the museum,]* | IMMERSION |
| van het ene naar het andere schilderij 'lopen' ging makkelijk. *[Translation: 'walking' from one painting to another was easy.]* Het systeem werkte goed *[Translation: The system worked well]* | EASE OF USE |
| **Participant 29 (Trial 1):** Het was makkelijk en helder. | EASE OF USE |

| Participant Feedback | Code |
|---|---|
| *[Translation: It was easy and clear.]*<br>Het enige wat mij af en toe stoorde was het tempo waarmee de portalen verschenen. Soms wilde ik gewoon even rond kijken, zonder meteen naar een nieuwe plek te willen.<br>*[Translation: The only thing that bothered me occasionally was the pace at which the portals appeared. Sometimes I just wanted to look around, without immediately wanting to go to a new place.]* | USABILITY ISSUES |
| **Participant 30 (Trial 2):** Het voelde voor mij een beetje omslachtig om steeds door die soort spiegels heen te stappen.<br>*[Translation: It felt a bit cumbersome for me to keep stepping through those kind of mirrors.]*<br>Ik vond de andere manier wat dat betreft prettiger. Maar het is bij die manier wel zo dat je echt naar de vloer moet blijven kijken. En dan ineens in een flits staat het schilderij voor je.<br>*[Translation: I found the other method more pleasant in that respect. But with that method, you do have to keep looking at the floor. And then suddenly in a flash the painting is in front of you.]* | USABILITY ISSUES |
| Deze tweede methode was minder soort van 'in your face'.<br>*[Translation: This second method was less sort of 'in your face'.]*<br>Dus beide hebben hun voordelen en nadelen. Ik weet niet welke mijn favoriet is.<br>*[Translation: So both have their advantages and disadvantages. I don't know which is my favorite.]* | REDUCED IMMERSION |
| **Participant 31 (Trial 2):** het stappen voelde toch iets lastiger omdat je soms ook weer naar achter moest<br>*[Translation: stepping felt a bit more difficult because sometimes you had to go backwards again]* | ORIENTATION ISSUES |

## Appendix C

# Information brochure and informed consent

# Information sheet user study

**Exploring Eye-Gaze Locomotion in Immersive Virtual Reality for Cultural Heritage exhibition.**

**Purpose of the Research:**
The aim of this research is to investigate how different navigation methods in virtual reality (VR) environments affects your experience. This research will is conducted in collaboration with the Rembrandthuis Museum.

**Benefits and Risks of Participation:**

- **Benefits**: Your participation will contribute to the development of more accessible and engaging VR experiences in museums and cultural heritage education. It will also provide valuable insights into designing user-friendly VR systems.
- **Risks**: There are minimal risks associated with this study. Some participants may experience mild discomfort or motion sickness during VR use. You may stop at any time if discomfort arises.
- This research project has been approved by the Information and Computer Science Ethical Committee of the University of Twente (approval number 220127).

**Procedures for Withdrawal from the Study:**
Your participation is entirely voluntary. You may withdraw from the study at any time without providing a reason. Withdrawal will not have any consequences, and any data collected up to the point of withdrawal will be securely deleted upon your request.

**Collection and Processing of Personal Information:**

- During the study, we will collect data such as physical movement of your head and feet, gaze data, and answers to questionnaires.
- All answers are stored anonymously. This means that we do not record your name, address, location data or contact details, so that answers cannot be traced back to a person.

**Usage and Safeguarding of Data:**

- **Confidentiality**: Your data will be stored on a system of the university and will be saved to a secure server accessible only to the research team.
- **Controlled Access**: Data will only be shared with the research team.
- **Dissemination**: Findings from this study may be used for the master thesis and could be used for in academic journals, conference proceedings, or shared with the Rembrandthuis Museum. No identifying information will be included in any publications.
-

**Contact Details:**

- **Researcher**:
  Henrico Pops
  EEMCS - University of Twente
  henricopops@gmail.com

- **CIS Ethics Committee**:
  If you have any concerns or wish to file a complaint regarding this study, you can contact the **secretary of the Information and Computer Science Ethics Committee:** **ethicscommittee-CIS@utwente.nl**

**Thank You:**
Thank you for considering participation in this research. Your involvement is crucial for advancing knowledge in immersive virtual reality and cultural heritage education

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## Consent Form

**YOU WILL BE GIVEN A COPY OF THIS INFORMED CONSENT FORM**

| *Please tick the appropriate boxes* | Yes | No |
|---|---|---|
| **Taking part in the study** | | |
| I have read and understood the study information. I have been able to ask questions about the study and my questions have been answered to my satisfaction. | ○ | ○ |
| I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason. | ○ | ○ |
| I understand that taking part in the study involves interacting with a virtual reality system, completing survey questionnaires, and allowing the recording of movement patterns, gaze data, and interaction behaviours, with any audio recordings transcribed and securely destroyed after use. | ○ | ○ |
| **Risks associated with participating in the study** | | |
| I understand that taking part in the study involves the following risks: potential mild discomfort or motion sickness during the virtual reality experience, which can be mitigated by taking breaks or discontinuing participation if necessary. | ○ | ○ |
| **Use of the information in the study** | | |
| I understand that the information I provide will be used for a master thesis, and potentially academic reports, presentations, and knowledge-sharing initiatives, such as collaboration with the Rembrandthuis Museum, while ensuring my data remains anonymized and used solely for research purposes as outlined in the information sheet. | ○ | ○ |
| **Optional:** | | |
| I agree that my answers can be quoted in research outputs | ○ | ○ |

**Signatures**

| ______________________ | ______________________ | ________ |
|---|---|---|
| Name of participant | Signature | Date |
| _________________________ | ___________________ | ________ |
| Researcher name | Signature | Date |

**Contact Information for Questions about Your Rights as a Research Participant**

If you have questions about your rights as a research participant, or wish to obtain information, ask questions, or discuss any concerns about this study with someone other than the researcher(s), please contact the Secretary of the Ethics Committee Information & Computer Science: ethicscommittee-CIS@utwente.nl

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